Schweizerische Eidgenossenschaft
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Swiss Federal Office of Energy SFOE

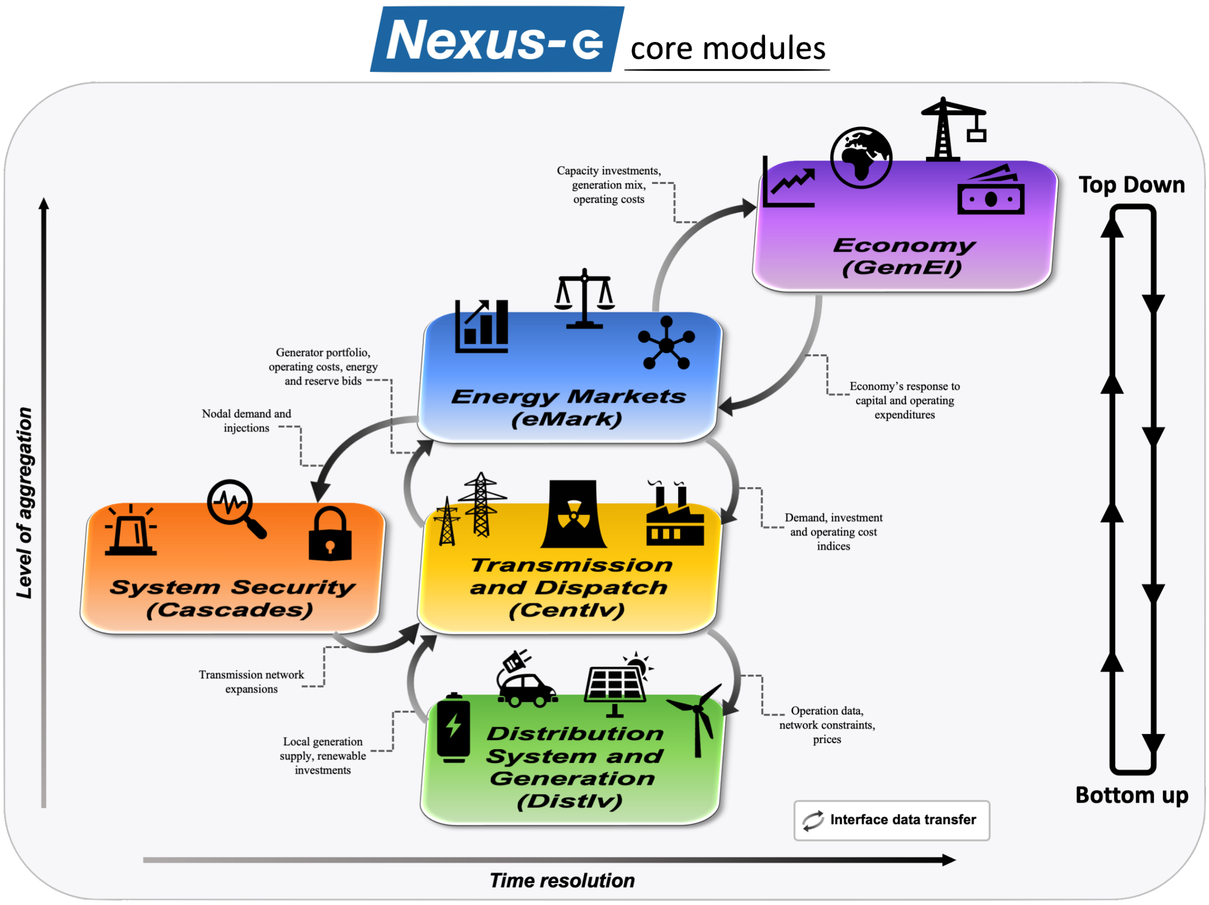
Department of the Environment,
Transport, Energy and Communication DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech

Final report

Nexus-e: Integrated Energy Systems Modeling Platform

Simulation Framework and Interfaces



Source: ESC 2019

Date: 27. November 2020

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
ETH Zürich
Energy Science Center
Sonneggstrasse 28, CH-8092, Zürich
www.esc.ethz.ch

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SFOE contract number: SI/501460-01

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.

A novelty of the Nexus-e platform is that it combines the core modules with automated interfaces to pass all necessary information between modules. The data transfer process within each interface is completely automated in code (hard-linked). The combined process and interfaces are designed to be modular and customizable so that different combinations of modules could be used together in future analyses. This report provides the description and documentation for all the interfaces along with the overall simulation process.

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.

Ein Novum der Nexus-e Plattform ist, dass es die Module mit automatisierten Schnittstellen kombiniert, um alle notwendigen Informationen zwischen den Modulen weiterzuleiten. Der Datentransferprozess innerhalb jeder Schnittstelle ist im Code vollständig automatisiert („hard-link"). Die Plattform und die Schnittstellen sind modular konzipiert und können für zukünftige Analysen angepasst werden, zum Beispiel, um verschiedene Kombinationen der Module zu erlauben. Dieser Bericht beinhaltet die Beschreibung und Dokumentation der Schnittstellen und des gesamten Simulationsprozess.

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.

Une nouveauté importante de la plateforme Nexus-e est qu'elle combine les modules de base avec des interfaces automatisées pour transmettre toutes les informations nécessaires entre les modules. Le processus de transfert des données au sein de chaque interface est entièrement automatisé en code (lien physique). Le processus et les interfaces combinés sont conçus pour être modulaires et personnalisables de sorte que différentes combinaisons de modules puissent être utilisées ensemble dans de futures analyses. Le rapport fournit la description et la documentation de toutes les interfaces ainsi que du processus de simulation global

Contents

Abbreviations

AC	alternating current
BSS	battery storage system
Cascades	Network Security and Expansion Module
CentIv	Centralized Investments Module
CGE	computable general equilibrium
DC	direct current
DistIv	Distributed Investments Module
DSM	demand-side management
DSO	distribution system operator
eMark	Electricity Market Module
EMP-E	Energy Modeling Platform for Europe
FCR	frequency containment reserve
FRR	frequency restoration reserve
GemEl	General Equilibrium Module for Electricity
GEP	generation expansion planning
MVA	mega-volt ampere
MW	megawatt
MWh	megawatt hour
OM	operation and maintenance
OOP	object-oriented programming
PV	photovoltaic
RES	renewable energy source
TSO	transmission system operator

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1 Introduction

The objective of this report is to describe the Nexus-e modeling framework and the associated processes to simulate the investments and operational decisions and their implications in the Swiss electric energy system for specific scenarios. In this work, a scenario simulation consists of four years (i.e. 2020, 2030, 2040, and 2050), which are referred to as scenario-years. The following sections introduce the Nexus-e framework including the main simulation 'loops', the interfaces that connect the modules, the database, the modules' initialization, and the process to move from one scenario-year to the next. Figure 1 provides an overview of the Nexus-e framework for a single scenario-year and serves as a useful reference to understand how the modules work together.

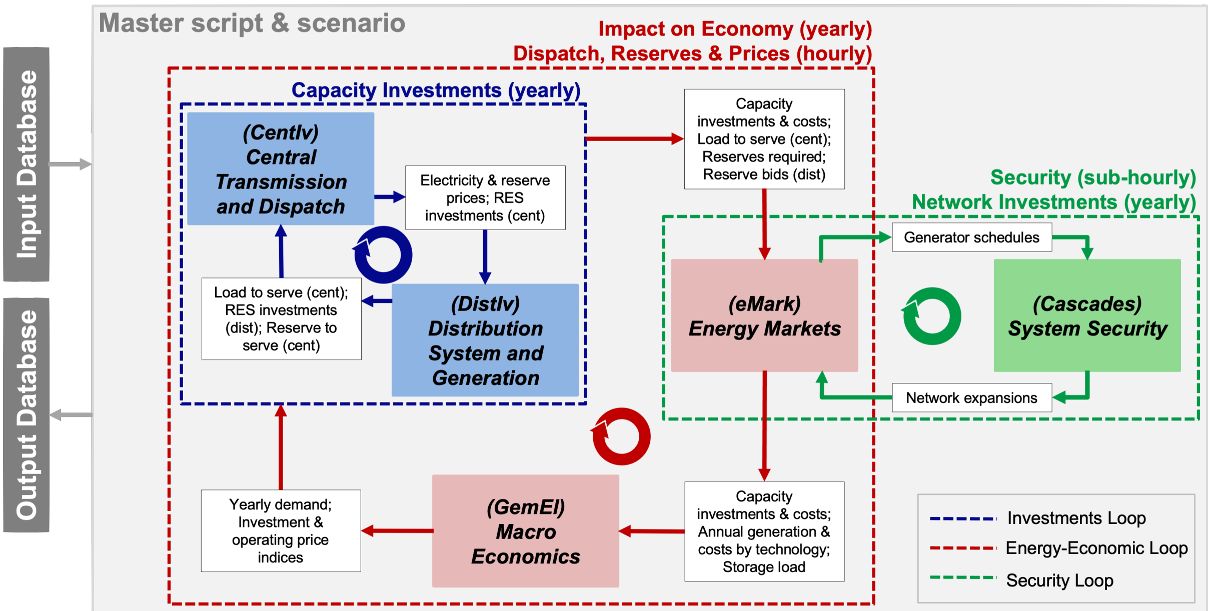

Figure 1: Overview of the Nexus-e framework including the five modules (colored boxes), the three 'loops' (colored arrows), and the interfaces (white boxes). Note that for visualization purposes some of the interfaces are combined in the figure.

1.1 Modules

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. 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 also can 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. CentIv has an important role within both the investment and energy-economic loops of the Nexus-e framework.

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, 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, a cascading failure simulations model and a transmission system expansion planning model.

1.2 Loops and Interfaces

To complete a simulation of a given scenario-year, the Nexus-e platform establishes the following three loops:

The Investments loop (blue) connects CentIv and DistIv with the purpose of modeling a coordinated generation expansion planning (generation expansion planning (GEP)) process at the transmission and distribution system levels. By combining these modules, the trade-offs from benefits and costs of investments in the centralized and distribution systems can be accounted for, yielding an expansion strategy for power generation that considers both layers.

The Energy-Economic loop (red) connects all modules with the exception of Cascades. The investment decisions made by CentIv and DistIv are used by eMark to determine the hourly generator schedules and operating expenses. Then, the investment costs, operating costs, and generation supply mix are handed over to the macroeconomic module GemEl, which re-establishes the equilibrium and adjusts the demand. The adjusted demand is sent back to the CentIv and DistIv modules to begin a new iteration of this loop. Convergence is reached when the annual demand result from GemEl does not change more than 2%.

The Security loop (green) connects eMark and Cascades with the purpose of assessing the system security after the Energy-Economic loop converges (i.e. after the investments in power generation are made). Furthermore, in the Security loop transmission system investments are proposed (upgrades of branches and transformers), if the reference system security is not satisfied. This loop serves as a security assessment and does not feedback to the other loops.

A novelty of the Nexus-e platform is that it connects the core modules with structured and automated interfaces to pass all necessary information between modules. The data transfer process within each interface is completely automated in code (hard-linked). The modules themselves are created using object-oriented programming (OOP) so that each module is encapsulated within an object that contains its own data (properties or attributes) and functions (methods or procedures). These interfaces are defined as one such function within each module's object and when called upon they package the required results data from their module into a specific data structure and send this structure as input to another module (i.e. the interface function is defined by the 'sending' module). So, when one module begins its simulation process, it will call all necessary interface functions defined by each of the other modules that it needs to receive input data from. Each of these functions extracts the appropriate results data from their modules, packages them in a predefined way, and sends them as input to the module starting its simulation process. In some cases, a single interface contains results data from multiple other modules (as is the case with the Investment-eMark interface where data from both CentIv and DistIv are sent to eMark) and also potentially contains results being passed through one module so that these data can later be sent to the next module in the simulation process (as is the case with the GemEl-Investments interface where some data from GemEl will be sent further on to eMark). The combined process and interfaces are designed to be modular and customizable so that different combinations of modules could be used together in future analyses.

The current Nexus-e modeling platform consists of the eight interfaces described briefly below:

Interfaces of the Investments loop

1. CentIv-DistIv interface: CentIv sends to DistIv results for the nodal demand, nodal electricity and reserve prices, total system reserve requirements, total electricity generated and total costs incurred by the newly invested units, electricity produced from RES and the RES target.
2. DistIv-CentIv interface: DistIv sends to CentIv results for the residual nodal demand and total distributed generation, residual reserve requirement and investments in non-dispatchable distributed generation units (i.e. photovoltaic (PV) in DistIv).

Interface of the Energy-Economic loop

3. GemEl-Investments interface: GemEl sends to the Investments loop (CentIv and DistIv) information on the yearly electricity demand along with changes in the price indexes of investments and generation costs.
4. Investments-eMark interface: the Investments loop (CentIv and DistIv) sends to eMark results for the investment decisions, reserve requirements, residual electricity demand, generator curtailments, demand shed, and hydro dam monthly storage levels.
5. Investments-GemEl interface: the Investments loop (CentIv and DistIv) sends to GemEl results for the fixed costs and investment costs by technology type, including newly built units, on both the transmission and distribution system levels (note that this interface is not illustrated in Figure 1 to improve visual clarity).
6. eMark-GemEl interface: eMark sends to GemEl the generation mix and operating costs by technology type along with the export/import of electricity.

Interfaces of the Security loop

7. eMark-Cascades interface: eMark sends to Cascades the generation dispatch, reserves, and export/import.
8. Cascades-eMark interface: Cascades sends to eMark a list of network upgrades.

The remainder of this report is ordered as follows: Section 2 discusses model linking principals found in recent literature[1] that were the basis for developing the linkage between bottom-up and top-down energy system models. The remaining Sections detail the Nexus-e platform by describing the steps necessary to simulate a single scenario-year and to progress from one scenario-year to the next. Section 3 introduces the initialization process implemented in the Nexus-e framework that is initiated prior to the first scenario-year simulation. Sections 4 (Investments loop), 5 (Energy-Economic loop), and 6 (Security loop) describe in detail the three loops and the associated interfaces that connect modules within each loop. Finally, Section 7 describes the post-simulation steps taken after one scenario-year simulation finishes and before the next scenario-year simulation begins.

[1] taken from [1]

2 Related work

Recently, there has been a tendency towards developing more comprehensive energy and economic modeling approaches.[2] The literature describes several approaches for linking existing top-down models with bottom-up models or for having a more multi-model/sector perspective [4, 5, 6, 7]. A typical example is the MESSAGE-MACRO model [8] that links the MACRO model to the MESSAGE energy supply model. Other examples are developed by [9] where the Swiss MARKAL residential model is coupled to GEMINI-E3, a global CGE model, as well as by [10] where the Emissions Prediction and Policy Analysis (EPPA) model developed at MIT includes a more detailed implementation of the energy sector. The EPPA model is a recursive-dynamic multi-regional general equilibrium model of the world economy. It is designed to develop projections of economic growth and anthropogenic emissions of greenhouse gases. The model includes a wide range of energy supply technologies and is linked to a climate-land ecosystems model.

A major drawback of top-down-bottom-up linkage can be the inconsistency in the behavioural assumptions of the models used. To resolve these inconsistencies, [11] calibrates the top-down model to the results of the bottom-up model. They adapt the transport sector representation in the EPPA CGE model to be consistent with the technological specification of MARKAL. Alternatively, [12] proposes to adjust the elasticities in the CGE model to the ones used in the bottom-up model. [13] proposes a method to include behavioural aspects in environmental policy analysis based on complexity dynamics and agent heterogeneity.

Another approach for linking top-down with bottom-up models aims at incorporating either a reduced bottom-up model within an existing top-down model or adding some equations coming from a top-down model inside an existing bottom-up model. [14] is an example in which the top-down and bottom-up models are completely integrated using the same modeling format. An example of the integration of a reduced top-down model in a bottom-up model can be found in [15], which incorporates a bottom-up specification of the electricity sector in a CGE model for the US economy. [16] integrates the macroeconomic model ETAMACRO [17] into the MARKAL model. All in all, these model linkage approaches have opened new possibilities to analyse multi-sector coupling [18]. For instance, [7] soft-links a TIMES model to a power system and a housing stock model to analyse the electrification of residential heating and the emissions of the residential sector. Other multi-sector bottom-up examples are: [19] models the inter-dependencies between gas and electricity networks, [20] studies decentralized multi-carrier energy systems and the role of storage technologies, and [21] explores reciprocal effects between energy demand and the evolution of the transport sector.

Originally, the linking and convergence procedure employed in Nexus-e was modeled using the methodology taken from [22]. This technique uses the equilibrium electricity price and demand from a top-down macroeconomic model to derive a linear approximation of the demand curve. The demand curve is then used to determine the generation mix in the bottom-up model, and total welfare is maximized. This technique is suitable for a highly aggregated bottom-up model with a yearly resolution as there is only one demand curve, and top-down and bottom-up models are built by the same modeler. However, if the bottom-up models have an hourly resolution like in Nexus-e, this means that the highly aggregated demand of the top-down model has to be split into hourly load curves magnifying the number of optimization problems by a factor of 8'760. Furthermore, since the modules in Nexus-e are developed by different researchers using different software, this methodology is not easily implemented. Therefore, a new approach for enabling this top-down and bottom-up connection was derived for Nexus-e that involves a recalibration of the supply/demand equilibrium based on the costs and generation mix of the bottom-up models (CentIv, DistIv, and eMark).

Summarizing, bottom-up and top-down methodologies differ in the treatment of temporal resolution,

[2]For an overview of approaches of the last 10-20 years, see [1], [2] and [3].

technological detail, aggregation or consideration of energy sectors, regional coverage, and energy system interactions with other external factors and with the economy. Existing modeling approaches tend to fall short in at least one of the following features: representing interactions with decentralized generation systems, modeling the details of the power system and the grid, providing a security and adequacy assessment of the grid, and studying long-term outlooks along with macroeconomic implications. Nexus-e closes this gap by explicitly including these important features in the individual modules and facilitating a holistic assessment by linking the interdisciplinary modules so feedbacks can be accounted for.

3 Initialization

Within the scope of this project a scenario consists of four years (i.e. years: 2020, 2030, 2040, and 2050), which we refer to as scenario-years. Furthermore, for calibration and validation purposes we simulate 2015 as a reference year.[3] We store and organize the Swiss power system physical data, time series data, and power demand data for the reference year and the scenario years in a MySQL database. In addition, the database stores the generator data per technology, including time series for the non-dispatchable units and hourly power demand for all neighboring countries of Switzerland. The modules do not pull data from the database in the initialization step, instead data are retrieved at the beginning of each module's run script. Moreover, some modules do not pull from the database since in these cases the necessary data are passed from one module to another (e.g. such as Cascades as described in Section 6).

The execution of the Nexus-e platform for one scenario simulation starts by establishing a connection with the MySQL database and creating a one to one copy of the database. This copy is created only once, before the first scenario-year is executed, and is used by the modules to pull data for each scenario-year[4]. Later, the post-simulation process appends this copy, so the modules can use the results from one scenario-year (generator investments, etc) in all subsequent scenario-years. In this way generator investments in 2020 will be included as existing units in 2030-2050. Next, all modules are initialized using module specific parameters, which are defined by the users, and each module's object is established.[5] An example of a user defined parameter is the "symMod" parameter in the Cascades module, which is used to control whether the alternating current (AC)-based or direct current (DC)-based representation is used within Cascades. Additionally, during the initialization step information about the current-scenario year is passed to each module, enabling them to pull the proper set of data from the MySQL database.

The most critical part of the Initialization step is the execution of GemEl which sets the starting point for demand in the current simulation scenario. GemEl begins with an initial point for the electricity demand from the available projections and adjusts based on the reference data from the input-output table for 2014 and GemEl's recalibration process. This adjustment mimics what GemEl does later during the scenario simulation when it adjusts the demand according to changes in prices, trade, and generation mix.

[3] Using a more recent year is not desirable since the most recent input-output table data used in GemEl is for 2014.
[4] This practice maintains the consistency of the original database and option to reproduce results.
[5] All modules use an OOP method to encapsulate all data and functions for a given module.

4 Investments loop

As part of the Investments loop (see blue area in Fig. 1), CentIv is interfaced with DistIv in order to model a coordinated GEP process at the transmission and distribution system levels. To this end, CentIv provides DistIv with 1) nodal demand, 2) nodal electricity and reserve prices, 3) total system reserve requirements, 4) total electricity generated and total costs incurred by the newly invested units as well as 5) electricity produced from RES along with the RES target. This information is used by DistIv to assess whether it is more economically viable to invest in new capacity at the distribution level or to use the available electricity from the transmission system. After the DistIv simulation is complete, it sends back the 1) residual nodal demand and total distributed generation, 2) residual reserve requirement and 3) investments in non-dispatchable distributed generation units (i.e. PV in DistIv) such that CentIv can re-evaluate investments, augment the reserve requirements (in case of investment in non-dispatchable generation units) and conduct a new centralized unit dispatch. Such a 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 each makes informed decisions based on the information exchange.

4.1 CentIv-DistIv interface

The CentIv-DistIv interface provides information on the operation and investments at the transmission system level. The data transferred from CentIv to DistIv are summarized in Table 1. These data enable DistIv to optimize the trade-off between making new investments at the distribution level and purchasing the electricity to supply the demand from the transmission system. Both CentIv and DistIv use an hourly resolution but simulate only every other day of the year to reduce the computational complexity[6]. We marked parameters that have an hourly resolution with an asterisk (*) to highlight this simplification. The CentIv and DistIv module reports provide more information regarding the implications of this time compression on the problem formulation.

Table 1: CentIv-DistIv module interface detail.

Data	Resolution	Unit	Description
Original Demand	hourly*, nodal	MW	Original transmission system demand
Electricity Price	hourly*, nodal	CHF/MWh	Dual variable of energy balance equation
Secondary Reserve Requirement	hourly*	MW	System secondary up/down reserve requirement
Secondary Reserve Price	hourly*	CHF/MWh	Dual variable of secondary reserve requirement equation
Total Net Generation	annual	MWh	Total net generation (generation - pump consumption) in CentIv
Investment Costs	annual	CHF	Investment and Fixed operation and maintenance (OM) costs of newly built units in CentIv
RES Production	annual	TWh	Total production from non-hydro RES (biomass, wind, PV) in CentIv
Original RES Target	annual	TWh	Target for production from non-hydro RES (biomass, wind, PV)

** uses an hourly resolution but simulates only every other day of the year to reduce the computational complexity*

DistIv separates the hourly demand for each distribution region and optimizes how these regional demands are supplied. New investments in distributed units could supply these demands or alternatively they can be supplied by purchasing from the centralized level at the electricity price. Simultaneously, DistIv uses the reserve requirement and centralized reserve price to enable distribution units to also

[6]We understand that such a reduced time step will incur a loss of accuracy in the results. However, preliminary test indicated that the trade-off between loss of accuracy versus improved computation time was acceptable.

supply reserves. As part of the optimization, DistIv also uses the annual net generation and investment costs from CentIv as a cost factor that is incurred in addition to the wholesale electricity price when demand is supplied by purchasing from the centralized level. Finally, the RES production and target from CentIv are used by DistIv when the scenario includes a requirement for renewable investments. In this case, the desired RES target must be met by the combination of RES generation in CentIv and DistIv (i.e. DistIv needs to at least fulfill the remaining target).

4.2 DistIv-CentIv interface

The DistIv-CentIv interface provides information on the operation and investments at the distribution level back to the centralized level. CentIv uses these data to adjust the demand and reserve requirements and re-evaluate the investments at the transmission level. The data transferred from DistIv to CentIv are summarized in Table 2.

Table 2: DistIv-CentIv module interface details.

Variable	**Resolution**	**Unit**	**Description**
Residual Demand	hourly*, nodal	MW	Residual demand (original demand minus distributed generation and demand-side management (DSM)/battery storage system (BSS) load shifting)
Residual Secondary Reserve Requirement	hourly*	MW	Residual hourly system secondary up/down reserve requirement
RES Production	annual	TWh	Total production from renewables in DistIv
Invested PV Capacity	annual, by unit type	MW	Annual PV investments during simulation year in DistIv
Distributed Generation	hourly*, nodal	MW	Generation from all units in the distribution system (existing and newly built)

* *uses an hourly resolution but simulates only every other day of the year to reduce the computational complexity*

The residual demand represents the remaining load that must be supplied by CentIv considering all distributed generation as well as DSM/BSS load shifting. Similarly, the residual reserve requirements need to be supplied by the centralized generators. The RES generation from DistIv is used if the scenario includes a renewable production requirement to calculate the remaining portion of this requirement that CentIv must supply. Finally, the PV capacity invested in by DistIv in this scenario-year is needed by CentIv to calculate the increased need for reserves to cover this added PV capacity. After each scenario-year simulation the invested distributed generation is appended to the input database and used by CentIv in the next scenario-year to account for expected injection from already existing distributed units.

5 Energy-Economic loop

The Energy-Economic loop is based on the underlying premise of Nexus-e, to combine multidisciplinary energy system models with iterative feedbacks into one overarching framework. In this loop, by combining the bottom-up optimizations of investment and operating decisions done in CentIv, DistIv, and eMark with the top-down economic equilibrium in GemEl, Nexus-e is able to account for the response of the economy to the changing infrastructure and investments in the electricity system. Similarly, Nexus-e can also assess how investments and operation of the electricity infrastructure would change in response to major shifts in the Swiss economy. An iterative convergence process is necessary for this loop since the modules cannot be solved simultaneously and each module depends on inputs from the other modules. This convergence process was developed based on the works discussed in Section 2 with the goal of improving how top-down economy models and bottom-up energy system models are linked. In Nexus-e, GemEl is the top-down CGE model and the other modules in the Energy-Economic loop are all considered bottom-up energy system models (i.e. CentIv, DistIv, and eMark).

As a starting point, GemEl provides the Investments loop (i.e. CentIv and DistIv) with the yearly electricity demand and the price indices for the generation technologies. As described in Section 4, CentIv and DistIv calculate the necessary investments in new generation capacities. Then eMark calculates the market dispatch, generator operating costs and electricity imports/exports, and sends them to GemEl along with the investment costs from CentIv and DistIv. GemEl then calculates a new annual demand and new generator price indices and passes these data back to CentIv and DistIv, beginning a new iteration of the Energy-Economic loop. This process continues until the yearly demand quantified by GemEl converges, i.e. the difference between the demand in the current iteration and the demand of the previous iteration (or the base case) is smaller than 2%.

Originally, the convergence procedure between top-down and bottom-up models was formulated using the methodology taken from [22]. However, since the Nexus-e bottom-up modules use a more detailed hourly resolution, an improved solution for enabling this top-down and bottom-up connection was derived. The Nexus-e convergence procedure involves a recalibration of the supply/demand equilibrium based on the costs and generation mix of the bottom-up models (CentIv, DistIv, and eMark).

In the bottom-up models, demand is given and supply is calculated endogenously. However, if the cost of the generation mix changes, this will have an impact on demand in GemEl. For example, if the bottom-up models show that replacing the supply of nuclear power leads to a massive investment in expensive technologies, this change will increase the electricity price in Switzerland and lead to a shift of the supply curve in GemEl and will result in a new supply/demand equilibrium. Figure 2 provides an illustration of the interactions between the modules in such a situation. In response to the higher costs of the new generation mix, industries and households will demand less electricity and try to substitute electricity with other energy sources (i.e. the supply curve shifts to the left implying an increase in generator costs). Once calibrated, the new equilibrium will yield the new annual Swiss electricity demand.

The information on investments, costs, imports, exports, and generation mix provided by CentIv, DistIv, and eMark are used in GemEl to recalibrate the generation technologies and distribution sector (see Figure 3) and determine the new electricity demand from the supply/demand equilibrium. For this recalibration, the information from the bottom-up models is used to replace the domestic generation in GemEl. While the domestic generation is fixed, the exports and imports are used as a starting point but allowed to adjust to the new demand. A change in demand is a reaction to changes in the electricity price caused by the change in generation mix and trade. In GemEl the domestic price of electricity is a mixture of the price of domestic generation and the price of imports. In Figure 3 an example is shown: on the left is the original situation with the costs for the domestic generation mix and the electricity distribution. On the right, the situation is shown after taking into account the results from the bottom-up models (a replacement of low cost nuclear power by more costly renewables). Also, according to the bottom-up

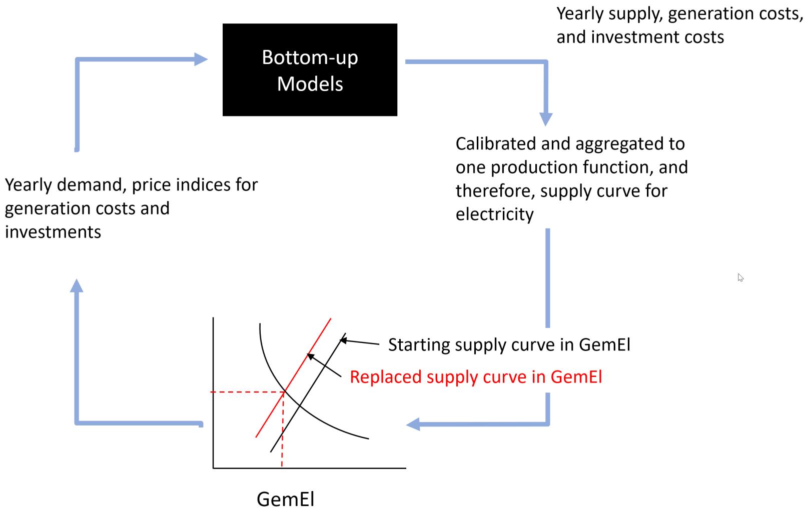

Figure 2: Interface between GemEl and bottom-up models.

models, domestic generation and exports are reduced and imports increased. The recalibration and changes in trade will lead to a shift of the supply curve in the top-down model (in the figure, the supply curve shifts to the left, implying an increase in generation costs) and demand goes down. The shift of the supply curve leads not only to a change in electricity demand but can also lead to a change in the prices of other goods and income of the households. These second-round effects, although smaller, can lead to further changes in the demand. This change in electricity demand could lead to different generator investment decisions, hence the need to connect and iterate these processes.

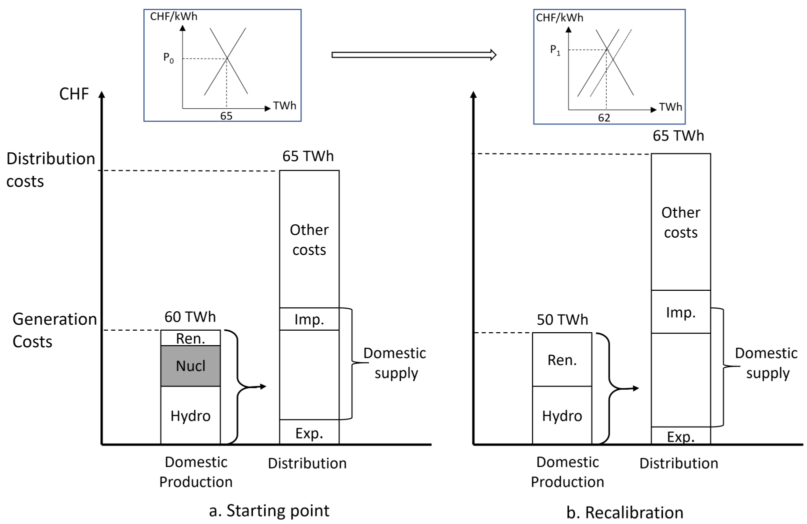

Figure 3: Recalibration of the electricity sector.

The detailed exchanges of data among the modules in the Energy-Economic Loop are given in the following subsections. Note that this loop also encompasses the Investments loop; however, the Investments loop interfaces were already presented in Section 4.

5.1 Investments-eMark interface

CentIv and DistIv are combined in the Investment loop to determine new capacity investments in Switzerland. Once these modules have completed the optimization of investment decisions, they provide information about these investments along with other parameters over an interface to eMark. Hence, this interface combines the results from two modules. Based on these data, eMark optimizes the generator schedules over the full year to supply the energy and reserve demands. Table 3 shows details of the data transferred in this interface.

Table 3: Investments-eMark module interface details.

Variable	**Resolution**	**Unit**	**Description**
Generator ID's	by unit	–	Generator database identifiers
Generator capacities	by unit	MW	Generator capacities
Generator variable costs	by unit	CHF/MWh	Total variable OM costs
System reserve requirements	hourly, zonal	MW	Requirement for each reserve product
Dam monthly storage levels	monthly	MWh	Aggregate Swiss energy volume in Dam reservoirs at the end of each month
Original demand	hourly, nodal	MWh	Original electricity load to serve
Residual demand	hourly, nodal	MWh	Residual load after distribution self-supply (DistIv)
Curtailments	hourly, nodal	MWh	Curtailments by CentIv of DistIv injections
Demand shed	hourly, nodal	MWh	Load shed by CentIv
Demand scale ratio	annual	fraction	Swiss load scale ratio from GemEl

The generator ID's, capacities and variable costs are used to update eMark and include any newly built units by CentIv and any adjustment to generator operating costs from the GemEl cost indices. Investments in DistIv are not modeled in eMark (i.e. not market participants) but their injections are accounted for in the residual load. CentIv also provides any update to the reserve requirements that could increase as new RES capacities are built in either CentIv or DistIv. The hydro dam storage levels at the end of each month are also updated by CentIv so that eMark will use the same seasonal pattern as CentIv. Note that CentIv optimizes the operation of Dams so the resulting seasonal pattern is not fixed to match the historical trend and can actually adjust to any future scenario. Monthly storage level targets are used to achieve the correct seasonal pattern while also allowing eMark autonomy on how it utilizes the dam units within each month. The nodal demand (i.e. original and residual), curtailments, and demand shed are provided by CentIv and DistIv so that eMark sets the proper hourly electricity demands (i.e. accounting for electricity supplied by DistIv, curtailments of DistIv injections required by CentIv, and any additional demand shed needed by CentIv). Two variables passed to eMark over this interface actually originate from the GemEl module but are first used within the Investments Loop: 1) the load scale ratio represents the reaction of demand to changes in the economy or energy sector, and 2) the generator variable costs that were adjusted by GemEl as a response to the expenses incurred in the electricity sector.

5.2 Investments-GemEl interface

The interface from the Investments loop to GemEl passes cost information for all generators, those newly built as well as those already existing, on both the transmission and distribution system levels. This information is mapped to the technology types in GemEl and used to recalibrate the module to reflect the new generation mix and costs. While the interface can be thought of as one process, in fact both CentIv and DistIv have individual functions that are called by GemEl to package and send the appropriate data. Having separate functions allows more flexibility within the framework (e.g. running a simulation without DistIv). Both functions provide to GemEl the same type of data for the generators in their respective modules. Table 4 shows details of the data transferred through the CentIv-GemEl and

DistIv-GemEl interfaces.

Table 4: CentIv-GemEl and DistIv-GemEl module interface details.

Variable	Resolution	Unit	Description
Investment cost	annual, by unit type	mill CHF	Investment cost per technology type
Fixed OM cost	annual, by unit type	mill CHF	Fixed OM cost per technology type

5.3 eMark-GemEl interface

The interface from eMark to GemEl passes information on the annual operating costs and generation share by technology type for new and existing generators. This information is mapped to the technologies used in the GemEl module and used to recalibrate GemEl to reflect the new generation mix and costs. Table 5 shows details of the data transferred in this interface.

Table 5: eMark-GemEl module interface details.

Variable	Resolution	Unit	Description
Variable OM cost	annual, by unit type	mill CHF	Variable OM costs per technology type
Generation share	annual, by unit type	megawatt hour (MWh)	Generation per technology type

5.4 GemEl-Investments interface

The GemEl-Investments interface provides feedback from the macroeconomic GemEl module to the bottom-up energy modules CentIv and DistIv about how the economy and consumers respond to the expenses incurred in the electricity system. The feedback is in the form of a change to the annual Swiss demand and a change to the operating and investment costs for generating units. Table 6 shows details of the data transferred in this interface.

Table 6: GemEl-Investments module interface details.

Variable	Resolution	Unit	Description
Total Swiss demand	annual	MWh	Yearly demand in Switzerland
Price index for variable OM costs	annual	–	Change in variable OM costs
Price index for fixed OM costs	annual	–	Change in fixed OM costs
Price index for investment costs	annual	–	Change in investment costs

CentIv compares the adjusted annual Swiss demand to the initial value of the annual demand pulled from the database and calculates their ratio as a scaling factor. The scaling factor is applied as a multiplier to the hourly nodal Swiss load profiles to re-scale them to match the adjusted total from GemEl. Similarly, new price indices provided by GemEl for operating and investment costs are used as a multiplier to reset all existing and candidate variable OM costs, fixed OM costs, and investment costs. CentIv and DistIv will both use the re-scaled load profiles and costs in the next iteration of the Energy-Economic Loop to re-evaluate the optimal investments.

6 Security loop

The objective of the Security loop is to provide a security assessment of the power system considering the investments (systemic transformations), which are proposed by the Investment and Energy-Economic loops (see Figure 1 for illustration of all loops). Moreover, if the security level of the system from the reference year (2015) is better than the currently assessed system (e.g. 2050), the Cascades module proposes investments in the transmission grid with the goal of reaching the reference security.

The Security loop consists of two interfaces: 1) the eMark-Cascades interface, 2) the Cascades-eMark interface. Through the eMark-Cascades interface, eMark provides Cascades with the power output of each unit (generation dispatch), the power exchange between Switzerland and the neighboring countries (imports and exports), and the procured power reserves (frequency containment reserve (FCR), positive and negative frequency restoration reserve (FRR)) that each generating unit in the power system provides. The time resolution of the data provided is one hour and the time horizon is one year. Additionally, eMark passes the power system physical data including the final list of power generation capacities to the Cascades module along with the final hourly power demand.

Through the Cascades-eMark interface, Cascades provides eMark with the lines/transformers that are proposed for upgrade (expansion plan). The list of lines/transformers to be built/upgraded is updated at each iteration between Cascades and eMark, and the full list is transferred to eMark. In other words, eMark is receiving a list of lines/transformers that consists of the lines/transformers from the current iteration and all previous iterations. The exchange of information between the modules continues until Cascades shows no need for further upgrades in the transmission system, i.e. after the reference security is reached. Furthermore, if there is no significant improvements to the security over the iterations, although new lines/transformers are proposed, the loop is stopped after a predefined iteration number is reached. The iteration process of the Security loop is shown in the flow chart of Figure 4. The exchange of data between Cascades and eMark is given in the following subsections.

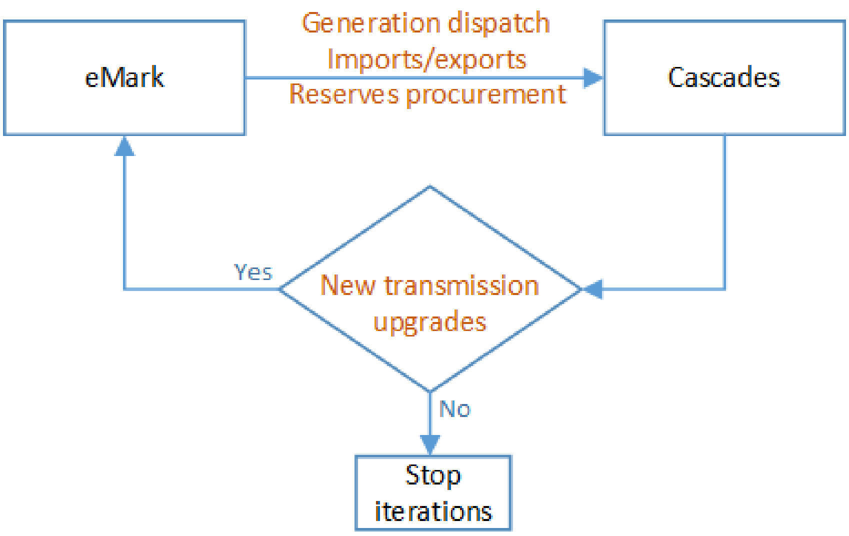

Figure 4: Flow chart of the Security loop.

The Security loop is performed after the Energy-Economic loop converges. Therefore, the proposed investments from the Cascades module for transmission system upgrades do not have any impact on the GEP during the current scenario-year. Furthermore, the proposed transmission expansion plan in one scenario-year is not carried forward to the next scenario-year. Instead, each scenario-year evaluates the need for transmission expansion independently. This assumption allows all scenarios and scenario-years to evaluate network security using a common existing transmission network and a common desired security threshold, enabling more straightforward comparisons between scenarios.

6.1 eMark-Cascades interface

The eMark-Cascades interface provides to the Cascades module a market-based generation dispatch, which is a feature that Cascades internally does not have. The market-based generation dispatch is used by the Cascades module to perform more accurate system security assessment and system expansion planning. The eMark-Cascades interface data consists of system physical (i.e. grid) and operational (i.e. dispatch) data, which are listed in Table 7.

Table 7: eMark-Cascades module interface details.

Variable	**Resolution**	**Unit**	**Description**
mpc version	–	–	Version for MatPower mpc structure, e.g., ’2’
mpc base mega-volt ampere (MVA)	–	MVA	Base MVA assumed for MatPower mpc, e.g., 100
mpc bus data	by bus	various	Bus data in MatPower format
mpc branch data	by branch	various	Line data in MatPower format
mpc gen data	by unit	various	Generator data in MatPower format
mpc gen cost data	by unit	various	Generator cost data in MatPower format
mpc gen info	by unit	various	Additional generator information
Load realization	hourly, nodal	megawatt (MW)	Nodal power demand in each hour
Generation positions	hourly, by unit	MW	Generator power injections in each hour
FCR procurements	hourly, by unit	MW	Generator power injections in each hour
Positive FRR procurements	hourly, by unit	MW	Generator power injections in each hour
Negative FRR procurements	hourly, by unit	MW	Generator power injections in each hour
Flow type	–	–	The power flow type (AC, DC)
Swiss zone number	–	–	The Swiss zone number

6.2 Cascades-eMark interface

The Cascades-eMark interface provides to the eMark module the transmission system upgrades, which are further used by the module in re-calculation of the market dispatch. The Cascades-eMark interface data consists of the physical characteristics of the proposed branch upgrades, as listed in Table 8.

Table 8: Cascades-eMark module interface details.

Variable	**Resolution**	**Unit**	**Description**
mpc branch data (new)	by branch	various	branches to be upgraded in MatPower format

7 Post-simulation process

Sections 4-6 describe the Loops for a single scenario-year, but since a full scenario simulation consists of four scenario-years, the scenario-year process needs to iterate (i.e. repeating the investment loop, energy-economic loop, and security loop). During this iteration, the Nexus-e framework communicates between the scenario-years using the database copy that was created during the initialization. At the end of each scenario-year simulation, a dedicated script updates this database copy with results that are relevant for the subsequent scenario-years. This script gathers the necessary results from the modules using functions defined within each module's object that act analogous to the interface functions used to send results between modules. The updates include: the new investments in centralized level generating capacities which should be part of the existing generation fleet for all future years, the additional reserve requirements needed to cover the newly added RES capacities, and the nodal profiles of distributed energy generation which CentIv will account for in all future years. In addition to the results pushed to the database, all modules save a full set of results data in separate files for each scenario-year. We use these data files for post-simulation analyses and data visualization.

8 Publications

The following list describes publications related to the Nexus-e platform:

- A poster presented at the 2018 Conference by the Energy Modeling Platform for Europe (EMP-E) [23] provides an overview of the Nexus-s integrated energy systems modeling platform.
- An article published in 2018 in the Energy Strategy Reviews journal [24] provides a thorough review of existing works related to modeling dimensions of the energy transition along with methods employed to combine various model types. The article then presents a proposal for an integrated linking of top-down and bottom-up models to represent: distributed generation and demand, operations of electricity grids, infrastructure investments and generation dispatch, and macroeconomic interactions.

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