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Report on energy grid modeling

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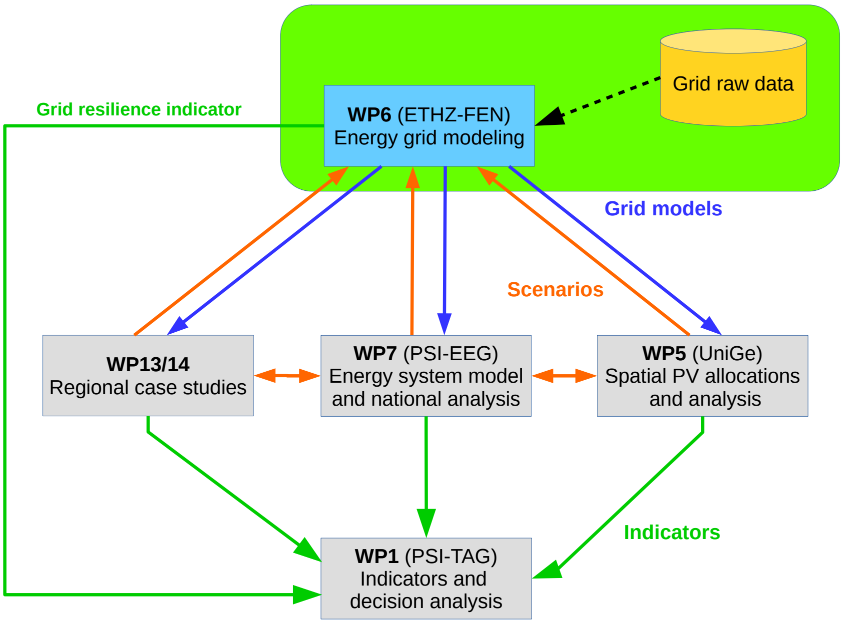


Zurich, November 30, 2022

1 Executive summary

This deliverable describes the Energy grid modeling framework (E-Grid) developed at ETHZ for the SURE modeling framework. In a first step, a need identification of each SURE partner has been carried out and harmonized with the objectives of the overall project. The primary focus, in line with the proposal, is an effective coupling of the grid models with the STEM energy system model. However, several more synergies have been identified with other partners and are being integrated, as the other workpackages progress.

For the electricity grid, a bottom up linear nodal transmission grid model of the European system is adopted for an aggregated representation of Switzerland. As a suitable granularity, the NUTS-2 level is chosen, while also respecting individual grid constraints of critical lines. The framework allows the recomputation of Available Transfer Capacity (ATC) values (import bounds) between Switzerland and its neighbors for different cooperation scenarios with the European union.

For the gas grid, a new nonlinear gas flow model has been established from a full European dataset, and adopted for studies of the Swiss gas transmission system. The model is demonstrated to perform efficient simulations of varying flow conditions ranging from normal operations to stress situations and outages in the gas grid. The implementation includes a webbrowser-based visualization tool, that has been developed for the gas network simulations. A first demonstration shows the effectiveness of flexible injections (gas storage units, synthetic fuels) to relieve contingency situations in the gas grid.

While the tools build on existing software, such as the tool FlexECO developed at ETHZ-FEN, and the results of previous studies, many new components were adopted or newly developed for SURE. The novelties include a hierarchical network model of the Swiss-European electricity grid with different aggregation levels, the unification of public data sources to create a Swiss-European gas flow model and the joint multi-energy modeling. As a result, E-Grid allows the a co-simulation of energy system scenarios in both the electricity and gas grid, for example, to study the impact of gas turbines or electrolyzers on both systems.

Overall, the E-Grid models are a solid foundation for the coupling with other SURE partners and the computation of security / resiliency indicators in the subsequent work packages. Based on the needs of the project, potential model extensions can be provided for both the electricity and the gas grid.

2 Zusammenfassung

Dieser Bericht beschreibt den an der ETHZ entwickelten Energienetz Modellierungsrahmen (E-Grid) für den SURE-Modellierungsrahmen. In einem ersten Schritt wurde eine Bedarfsermittlung der einzelnen SURE-Partner durchgeführt und mit den Zielen des Gesamtprojekts in Einklang gebracht. Das Hauptaugenmerk liegt dabei auf einer effektiven Kopplung der E-Grid-Netzmodelle mit dem STEM-Energiesystemmodell. Es wurden jedoch mehrere weitere Synergien mit anderen Partnern identifiziert, die mit dem Fortschritt der anderen Arbeitspakete integriert werden.

Für das Stromnetz wird ein lineares nodales Bottom-up Netzmodell des europäischen Systems für eine aggregierte Darstellung der Schweiz verwendet. Als geeignete Granularität wurde die NUTS-2-Ebene gewählt, wobei auch die individuellen Netzbeschränkungen durch kritische Leitungen innerhalb der Schweiz berücksichtigt wurden. Der Rahmen ermöglicht die Neuberechnung von ATC-Werten (Importgrenzen) zwischen der Schweiz und ihren Nachbarländern für verschiedene Kooperationsszenarien mit der Europäischen Union.

Für das Gasnetz wurde ein neues nichtlineares Gasflussmodell auf der Grundlage eines vollständigen europäischen Datensatzes erstellt und für Studien des Schweizer Gasübertragungsnetzes verwendet. Das Modell kann unterschiedlicher Flussbedingungen effiziente simulieren, und dabei Situationen abbilden, die vom Normalbetrieb bis zu Stresssituationen und Ausfällen im Gasnetz reichen. Die Umsetzung beinhaltet ein Webbrowser-basiertes Visualisierungstool, das für die Gasnetzsimulationen entwickelt wurde. Eine erste Demonstration zeigt die Wirksamkeit flexibler Einspeisungen (Gasspeicher, synthetische Brennstoffe) zur Entlastung von Engpasssituationen im Gasnetz.

Während die Werkzeuge auf bestehender Software, wie dem an der ETHZ-FEN entwickelten Tool FlexECO, und den Ergebnissen früherer Studien aufbauen, wurden für SURE viele neue Komponenten angepasst oder neu entwickelt. Zu den Neuerungen gehören ein hierarchisches Netzmodell des schweizerisch-europäischen Stromnetzes mit verschiedenen Aggregationsstufen, die Vereinheitlichung öffentlicher Datenquellen zur Erstellung eines schweizerisch-europäischen Gasflussmodells und die gemeinsame Multi-Energie-Modellierung. Dadurch ermöglicht E-Grid die Co-Simulation von Energiesystem-Szenarien sowohl im Strom- als auch im Gasnetz, zum Beispiel um die Auswirkungen von Gasturbinen oder Elektrolyseuren auf beide Systeme zu untersuchen.

Insgesamt bilden die E-Grid-Modelle eine solide Grundlage für die Kopplung mit anderen SURE-Partnern und die Berechnung von Sicherheits-/Resilienzindikatoren in den nachfolgenden Arbeitspaketen. Je nach den Erfordernissen des Projekts können potenzielle Modellerweiterungen sowohl für das Strom- als auch für das Gasnetz bereitgestellt werden.

Acronyms

ATC Available Transfer Capacity. 1, 2

DC Direct Current. 11

E-Grid Energy grid modeling framework. 1, 2, 7, 14, 19

ENTSO-E European Network of Transmission System Operators for Electricity. 7

ENTSO-G European Network of Transmission System Operators for Gas. 18, 20, 21

EV Electric Vehicle. 16

FlexECO Flexible Economic Optimization Framework. 15

GSK Generation Shift Keys. 11

PTDF Power Transfer Distribution Factor. 11

PV Photo Voltaic. 8

STEM Swiss TIMES Energy system Model. 4, 14, 19, 24

TYNDP Ten Year Network Development Plan. 7

3 Need identification of SURE partners

Based on the SURE project plan, interactions with the research partners regarding energy grid modeling have been identified. The interactions are illustrated in Figure 1.
To identify the energy grid modeling needs as well as synergies with the activities of the research partners, interviews and discussions have been conducted, resulting in the following findings:

- Meetings with PSI-EEG have been carried out to identify the interface to import scenarios and export relevant indicators and constraints. As a main result, FEN will receive information on electricity demand and production for representative hours on a Swiss zonal (NUTS-2) level. These scenarios include normal operation as well as stress/shock scenarios created by Swiss TIMES Energy system Model (STEM) (see Deliverable 2.1 for details). The parameters will be disaggregated to individual nodes of the electricity grid and simulated, together with appropriate models of the neighboring European countries. Furthermore, constraints should be computed for selected variable parameters, e.g., the zonal production or demand. The aggregated constraints will be used by PSI-EEG in the STEM model on a NUTS-2-level to ensure the secure grid operation and mitigate overloadings.

- Similarly, together with PSI-EEG, exchanges have taken place to identify constraints on the gas grid operation. A European gas grid infrastructure model will be adopted to incorporate flow limits of the Swiss transmission system as well as the broad ENTSO-G network. The model will also assess, how hydrogen can be transported in part of the network during a parallel operation of both energy carriers.

- Meetings with TEP have been carried out, to identify modelling needs, in particular to residiential gas grids and heat grids. For the Zurich case study in WP14, part of the future Zurich heat grid will be modelled for the cost and feasibility analysis of substituting part of the gas grid with heat grids.

- Additional dedicated modeling meetings have been carried out with SUPSI and UNIGE. The main focus there is residential and regional electricity grids. The partners have currently no need for additional grid models, although work has not yet started for all related subtasks. The main focus in the subsequent interactions with these partners will be to harmonize the models and scenario parameters used in the assessments.

From these meetings, the main modeling needs of the SURE project are identified as follows:

- Development of an integrated model of the Swiss electricity and gas grid.

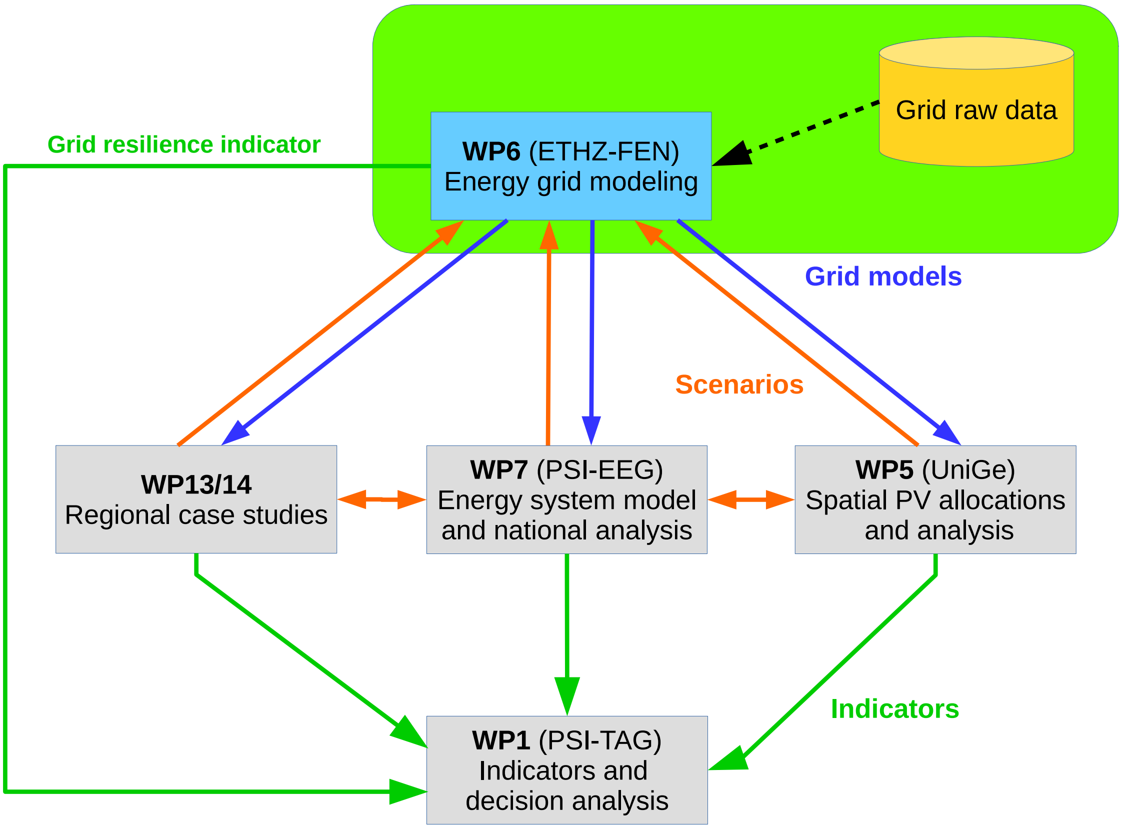


Figure 1: Interaction of WP6 with SURE partners from other workpackages. The interactions include energy grid models, calibration scenarios and indicators.

- Provide the models using a suitable zonal granularity of Switzerland and the model linkage in the PSI-EEG model STEM.
- Represent all relevant constraints of energy (electricity and gas) flows.
- Allow a detailed model simulation of individual scenarios for technical resiliency assessments using static grid modeling as well as disturbance and stress scenarios (e.g., outage, transit flows).
- The level of detail for the modeling of thermal grids depends on the regional characteristic of investigated case study. This investigation as well as the implementation is carried out in WP14. However, the heat grid model will build on the gas flow simulation framework, developed for the gas grid model in this deliverable.

As a result, this deliverable focuses on the modeling aspects for electricity and gas grids and the basic model characteristics for quantitative investigations of energy flows. Subsequent deliverables focus on the model aggregation and interfaces to other models (D6.2) and the security / resiliency analysis (D6.3).

4 Electricity grid modeling

This section describes the derivation of the electricity grid model used in SURE project. An overview of the modeling approach is shown in Figure 2. The main output is an aggregated model of the Swiss and European transmission grid for integration in the modeling framework STEM, as well as the tools of other SURE partners (EXPANSE, Building Stock Model).

4.1 European and Swiss grid model data

4.1.1 Transmission grid model

The grid model used includes the transmission grid of Switzerland and 18 other European countries (AT, DE, FR, IT, BE, CZ, DK, ES, GB, HU, LU, NL, NO, PL, PT, SE, SI, SK). The transmission grid model of all european countries is modelled based on a public [10] dataset of the European electricity grid and is illustrated in Figure 3. Additionally, the plausibility of the transmission network within Switzerland is also checked. For the scenario years 2025, 2030, 2035 and 2040, all grid expansion measures planned for the coming years in accordance with the European Ten Year Network Development Plan (TYNDP) Scenarios [3] or the Swissgrid grid investment plans [12] are included in the grid model. The 2040 grid situation serves as starting point for 2045 and 2050 as well. For all years, further grid upgrades will be identified as part of an iterative process between STEM and E-Grid.

The Swiss transmission grid is illustrated in Figure 4 and is embedded in the European grid model. Most of the other European countries are aggregated and represented by the import, export and transit flows towards Switzerland. The aggregation procedure is outlined in Section 4.2. Furthermore, the Swiss model is split into 7 zones represented by the statistical NUTS-2 regions in Switzerland to represent the different types of production and demand in each zone. The model captures network constraints between and within each zone, as well as the impact of imports from the 4 neighboring countries.

4.1.2 Power plant model

The initial nodal power plant fleet in Switzerland is based on a data set from the previous research project *Assessing future electricity markets* (AFEM) project [1] and is then scaled up to the aggregated values of the power plant capacities used in STEM. For the European power plant capacities, data is used from the TYNDP-2022 dataset published by European Network of Transmission System Operators for Electricity (ENTSO-E). An appropriate scenario is selected for the European countries, with the goal to be consistent with the STEM development path. The scenarios are also compared to the findings of the SWEET-CROSS project. For flexible generation, the data includes nuclear power plants, gas and steam combined cycle power plants, biomass plants, small combined heat and power plants, waste incineration plants

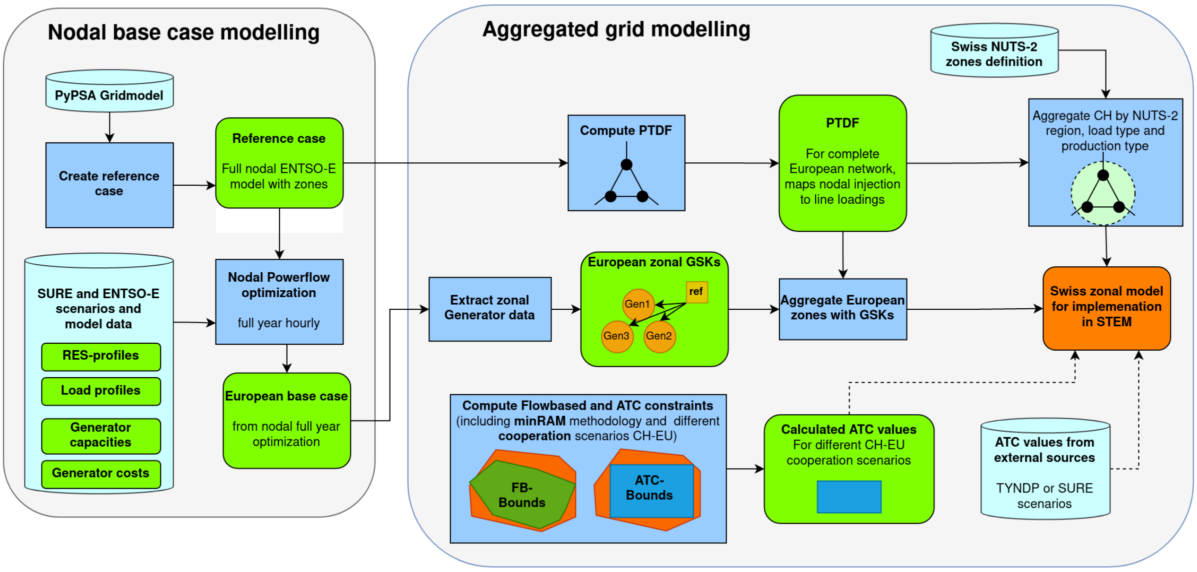


Figure 2: Overview of the electricity transmission grid modeling performed in WP6. The modeling is carried out in two steps: (1) parameterization of a full European nodal grid model and computation of a full year hourly base case; (2) aggregation to a Swiss zonal model for export and implementation in the SURE modeling framework STEM.

and district heating plants. Renewables such as wind, solar and Photo Voltaic (PV) are included as fixed injections, with the option of curtailment. The nodal power plant fleet in the other European countries, the data set of **PyPSA** forms the basis. For the scenario years 2025, 2030, 2035 and 2040, the capacities of the individual plants per power plant type are scaled up based on the scenario data from TYNDP-2022.

This process, of mapping aggregated power plant data from the first dataset (TYNDP) to a nodal grid model (PyPSA) is a *regionalisation* process that can not be fully automated, but requires individual plausibility checks and adjustments. The main difficulties include:

- Handling of different power plant types and names between the two data sets.
- Large changes between scenario years, including the introduction of power plants in a country, that previously had no or only very little representatives of the same type.
- Large changes in power plant capacity in locations requiring grid reinforcements.

For Switzerland, the initial power plant fleet only serves a starting point for the allocation within the different Swiss zones (NUTS-2 regions). The Swiss power plant fleet will be adjusted and updated within the SURE project to accomodate the various objectives, indicators and constraints of the model.

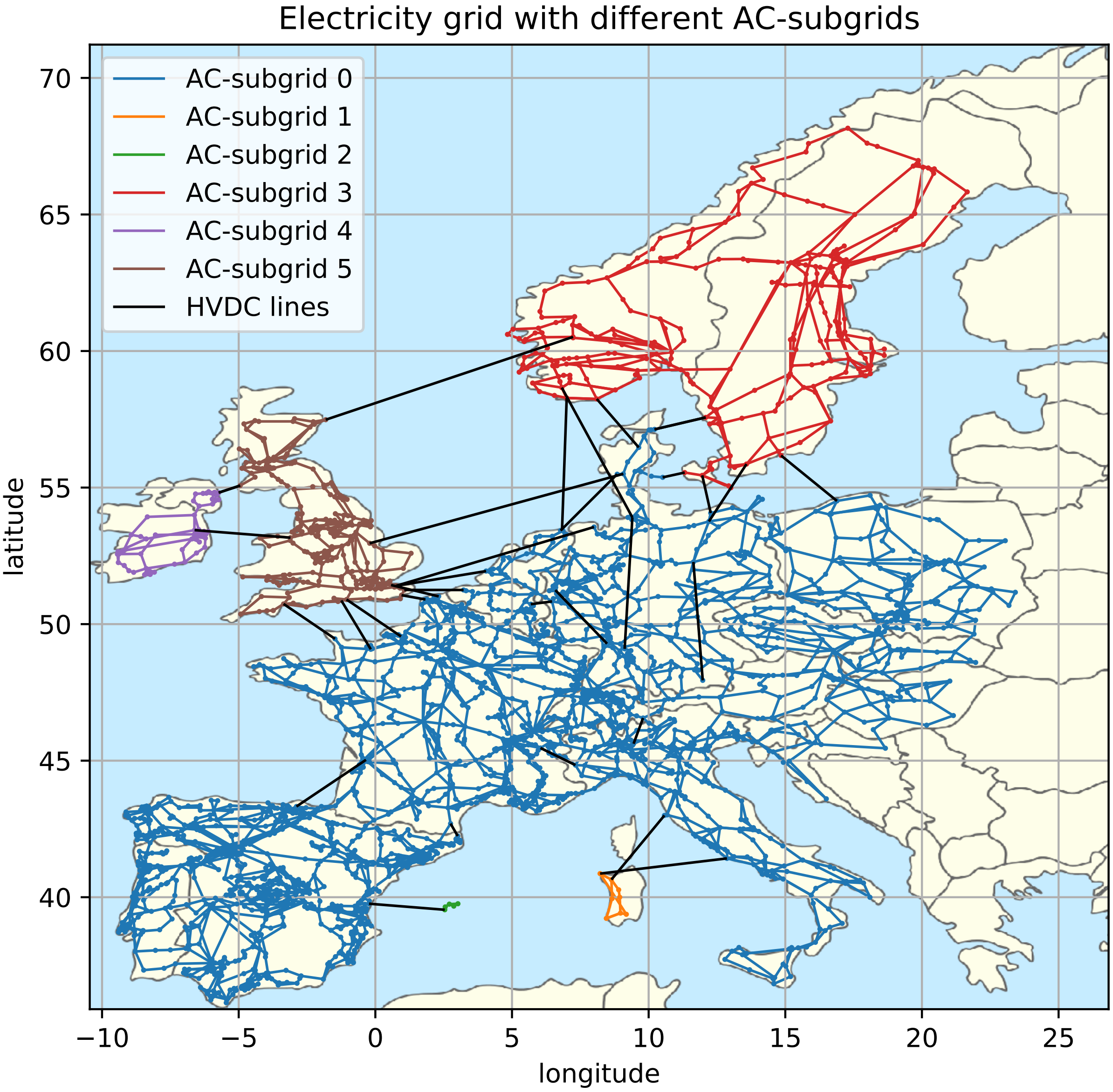


Figure 3: Illustration of the European nodal grid model with different synchronous zones and HVDC links. The illustration includes future grid upgrades (e.g., the North-South HVDC connection in Germany). The nodal model is initially parameterized with power plant, load and weather scenarios from TYNDP. When coupled with the other SURE models, these scenarios will investigated development paths.

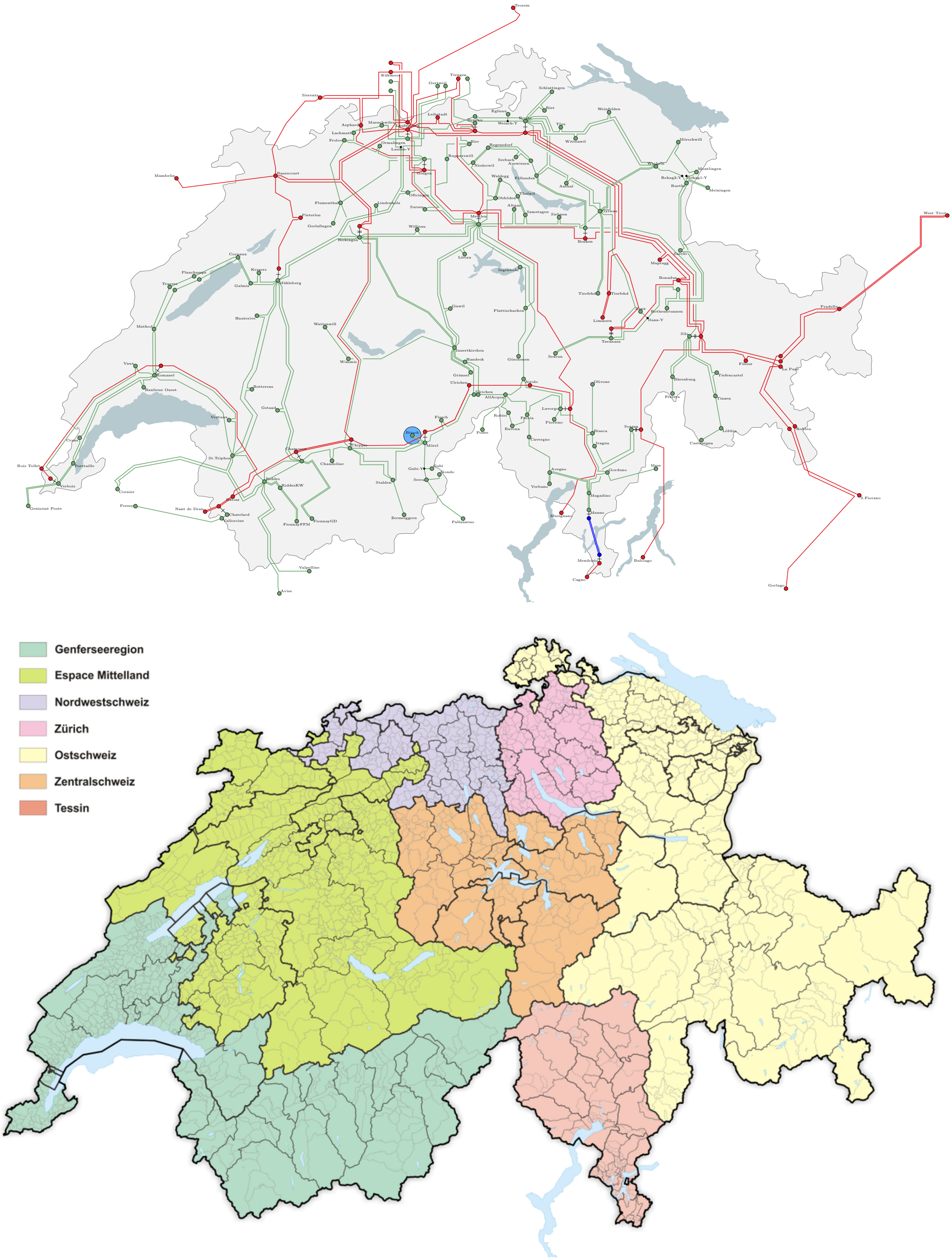


Figure 4: Illustration of the Swiss nodal transmission grid model used for investigations in the SURE project (top) and the corresponding NUTS-2 regions (bottom, *Source: Wikipedia*). The regional grid model prepared for STEM is based on different variables for different types of production and demand in each zone. The model captures network constraints between and within each zone, as well as the impact of imports from the 4 neighboring countries. Furthermore, the model captures the impact of transit flows from the European union (e.g. between Germany and Italy).

4.2 Grid modeling and aggregation

The nomenclature for the electricity grid modeling is provided in Table 1.
As outlined in Figure 2, the modeling is carried out in two steps:

1. parameterization of a full European nodal grid model and computation of a full year hourly base case;
2. aggregation to a Swiss zonal model for export and implementation in the SURE modeling framework STEM.

The grid modeling and aggregation is derived with variables that vary over time. The time index varies over all hours of a reference year (1 to 8760) or another reference time frame (1 to 288 like in STEM). Many variables change hourly (e.g., the line flows or power injections for different hours in different scenarios) or monthly (power plant availabilities, Generation Shift Keys (GSK), zonal Power Transfer Distribution Factor (PTDF)). For the purpose of readability, the time time index is omitted.

4.2.1 Nodal PTDF-Model

The starting point of the grid modelling is given by the the linear Direct Current (DC) load flow model. This model allows for a given distribution of net distribution of the net feed-in at each node, to calculate all the unknown variables of the network, in particular the load on the individual lines. For details on DC load flow modelling, please refer to the literature [9]. Important, however, is that due to the linearity, an explicit solution by determining the so-called PTDF matrix is possible:

$$\mathrm{f} = \mathrm{M_n p_n} \quad . \tag{1}$$

The vector f represents the active power flow over each of the n_l transmission lines, the vector $\mathrm{p_n}$ represents the net injection at each of the n_n Nodes, and the $n_\mathrm{l} \times n_\mathrm{n}$ matrix $\mathrm{M_n}$ represents the nodal PTDF-matrix. The net injections consist of production (counted positive) and loads (counted negative),

$$\mathrm{p_n} = \mathrm{p_{gen,n}} - \mathrm{p_{load,n}} \quad . \tag{2}$$

Table 1: Nomenclature for the electricity grid modeling

Symbol	Description	unit
$\Delta\mathrm{f}$	correction factor line flows	MW
f	vector of active power flow	MW
$\mathrm{f_{max}}$	vector of maximum line flows	MW
G	GSK-Matrix	1
$\mathrm{M_n}$	nodal PTDF-matrix	1
$\mathrm{M_z}$	zonal PTDF-matrix	1
$\mathrm{p_n}$	vector of net injections	MW
$\mathrm{p_z}$	vector of zonal injections	MW

Each element of the nodal PTDF matrix indicates how the injection at the corresponding node impacts the flow over the corresponding line. By equation (5), the line load for a grid use case can be determined through matrix multiplication without the need for optimisation or numerical solution. Since each line has a maximum load, which is represented in the vector $\mathbf{f}_{\mathrm{max}}$, the following grid constraints must be respected:

$$-\mathbf{f}_{\mathrm{max}} \leq \mathbf{f} \leq \mathbf{f}_{\mathrm{max}} \quad . \tag{3}$$

To perform the grid aggregation, the network with n_{n} nodes is first partitioned into n_{z} zones. The zones include all current European market zones that are also used in the TYNDP data:

`'AL00', 'AT00', 'BA00', 'BE00', 'BG00', 'CH00', 'CY00', 'CZ00', 'DE00', 'DKE1', 'DKW1', 'EE00', 'ES00', 'FI00', 'FR00', 'FR15', 'GR00', 'GR03', 'HR00', 'HU00', 'IE00', 'ITCN','ITCS', 'ITN1', 'ITS1', 'ITSA', 'ITSI', 'LT00', 'LUB1', 'LUF1', 'LUG1', 'LV00', 'ME00', 'MK00', 'MT00', 'NL00', 'NOM1', 'NON1', 'NOS0', 'PL00', 'PT00', 'RO00', 'RS00', 'SE01', 'SE02', 'SE03', 'SE04', 'SI00', 'SK00', 'TR00', 'UA01', 'UK00', 'UKNI'`

Furthermore, the Swiss zone is partitioned into the 7 NUTS-2 regions shown in Figure 4:

`'CH01','CH02','CH03','CH04','CH05','CH06','CH07'`

The zonal incidence-matrix $\mathbf{1}_{\mathrm{nz}}$ is a $n_{\mathrm{z}} \times n_{\mathrm{n}}$ matrix and denotes the mapping of nodes to zones. The entries of the matrix in row i and column j are 1 if node j belongs to zone i, otherwise the entries are 0. With the zonal incidence matrix, the vector of the total net feed-in in each zone can be determined,

$$\mathbf{p}_{\mathrm{z}} = \mathbf{1}_{\mathrm{nz}}\mathbf{p}_{\mathrm{n}} \quad , \tag{4}$$

by simply summing the net injections in each zone.

Additionally, the available flexible injection is determined for each node and arranged in the so-called GSK-matrix. The GSK-matrix $\mathbf{G}$ is a $n_{\mathrm{n}} \times n_{\mathrm{z}}$ matrix, whose entry in row i and column j reprensents the flexible injection at node i, divided by the total flexible injection in zone j, if the node i lies in zone j. All other entries are zero. For Switzerland, the entries of the GSK-matrix are not simply the aggregate of all flexible generators, but are differentiated by production type. Depending on the options for development paths of the the energy system planning within SURE, the GSKs and thereby the distribution of the net-injections to the nodes are differentiated as follows:

- by production type (gas, nuclear, hydro-run-of-river, pumped-hydro, hydro-dam, biomass, fuel cells)
- by load type (residential, commerce, industry, electrolyzers, electric mobility).

The GSK-matrix distributes a vector of zonal injections to the nodes in each of the corresponding zones. Besides, the GSK-matrix allows to define the zonal PTDF-matrix,

$$\mathbf{M}_\mathrm{z} = \mathbf{M}_\mathrm{n}\mathbf{G} \quad , \tag{5}$$

a $n_\mathrm{l} \times n_\mathrm{z}$ matrix, that distributes the total net injection of each zone to all the lines in the network.

The network constraints are determined for different scenarios and time steps. To this end, the optimal DC load flow of the nodal grid model is determined for each development scenario, each support year and each hour of the support year. The result is also referred to as the base case load flow. The vector of base case nodal net injections is denoted as $\mathbf{p}_\mathrm{n}^0$ and the corresponding vector of base case zonal net injection is determined as:

$$\mathbf{p}_\mathrm{z}^0 = \mathbf{1}_\mathrm{nz}\mathbf{p}_\mathrm{n}^0 \tag{6}$$

The network constraints computed for the STEM model limit the zonal net injection based on the line limits in the nodal network model. There are multiple nodal injections $\mathbf{p}_\mathrm{n}$ (and therefore also line loadings), that result in the same given zonal net injection $\mathbf{p}_\mathrm{z}$. For a unique calculation procedure, the European ACER-guidelines (also used for the flow-based market coupling) provide a definition, how the connection between zonal and nodal model is carried out. First, the nodal and zonal net injections are expressed as variations around the base case power flow, $\Delta\mathbf{p}_\mathrm{n}$ and

$$\mathbf{p}_\mathrm{n} = \mathbf{p}_\mathrm{n}^0 + \Delta\mathbf{p}_\mathrm{n} \tag{7}$$

$$\mathbf{p}_\mathrm{z} = \mathbf{p}_\mathrm{z}^0 + \Delta\mathbf{p}_\mathrm{z} \quad . \tag{8}$$

The deviations $\Delta\mathbf{p}_\mathrm{n}$ and $\Delta\mathbf{p}_\mathrm{z}$ are coupled via the GSK-matrix,

$$\mathbf{p}_\mathrm{n} = \mathbf{p}_\mathrm{n}^0 + \Delta\mathbf{p}_\mathrm{n} \quad . \tag{9}$$

$$= \mathbf{p}_\mathrm{n}^0 + \mathbf{G}\cdot\Delta\mathbf{p}_\mathrm{z} \quad . \tag{10}$$

$$= \mathbf{p}_\mathrm{n}^0 + \mathbf{G}\cdot(\mathbf{p}_\mathrm{z} - \mathbf{p}_\mathrm{z}^0) \quad . \tag{11}$$

This allows to compute the flow in each transmission line as

$$\mathbf{f} = \mathbf{M}_\mathrm{n}\mathbf{p}_\mathrm{n} \quad . \tag{12}$$

$$= \mathbf{M}_\mathrm{n}(\mathbf{p}_\mathrm{n}^0 + \mathbf{G}\cdot(\mathbf{p}_\mathrm{z} - \mathbf{p}_\mathrm{z}^0)) \tag{13}$$

$$= \mathbf{M}_\mathrm{n}(\mathbf{p}_\mathrm{n}^0 - \mathbf{G}\mathbf{p}_\mathrm{z}^0) + \mathbf{M}_\mathrm{n}\mathbf{G}\mathbf{p}_\mathrm{z} \tag{14}$$

$$= \Delta\mathbf{f} + \mathbf{M}_\mathrm{z}\mathbf{p}_\mathrm{z} \tag{15}$$

and the resulting **network constraints on the zonal net-injections**

$$-\mathbf{f}_\mathrm{max} - \Delta\mathbf{f} \leq \mathbf{M}_\mathrm{z}\mathbf{p}_\mathrm{z} \leq \mathbf{f}_\mathrm{max} - \Delta\mathbf{f} \quad . \tag{16}$$

The correction factor of the line flows,

$$\Delta\mathbf{f} = \mathbf{M}_\mathrm{n}(\mathbf{p}_\mathrm{n}^0 - \mathbf{G}\mathbf{p}_\mathrm{z}^0) = \mathbf{M}_\mathrm{n}(I - \mathbf{G}\mathbf{1}_\mathrm{nz})\mathbf{p}_\mathrm{n}^0 \quad , \tag{17}$$

captures the difference between the line flows from the base case in the nodal model and the zonal model.

For Switzerland, the constraints (16) have the following characteristics and interpretations:

- If the Swiss component of the zonal injection $\mathbf{p}_z$ are set to zero, the flows on the Swiss lines correspond to the loadings from the European loop flows (trades within a zone causing flows through Switzerland) and transit flows (trades between other zones, causing flows through Switzerland).
- If the zonal injections are equal to the base case $\mathbf{p}_z^0$, the line loading is exactly the same as in the nodal base case predictions $\mathbf{p}_n^0$. For all other zonal injections, the injections are varied around the base case using the GSK-allocation.
- For the European zones with flow-based market coupling, the correction factor $\Delta\mathbf{f}$ in (17) may become quite large due to non-dispatchable generation (wind and PV), that is not captured in the GSK-matrix. However, with the finer the zonal granularity within Switzerland, the correction factor $\Delta\mathbf{f}$ tends to be small for the Swiss lines and may be neglected. The reason is, that in (17) either the PTDF-entries in $\mathbf{M}_n$ for European nodes are small or the difference $\mathbf{p}_n^0 - \mathbf{G}\mathbf{p}_z^0$ for Swiss nodes is small. The difference will be checked in the detailed electricity grid simulation performed during the coupling of E-Grid and STEM. If needed, the parameter will be updated to achieve a more accurate aggregated model representation in STEM.
- As noted, the entries GSK-matrix in Switzerland are not simply the aggregate of all flexible generators, but are differentiated by production type.

In summary, the derived model (16) is very close to a redispatch model. It captures line contingencies within Switzerland, has a reasonable zonal granularity and differentiates between different production types. It also includes imports and transit flows from the European system, allowing to model international trades as well as increased system stress due to import bounds or high transit flows.

The model is implemented in the multi-energy planning and dispatch tool FlexECO [4], continuously developed at ETHZ and adopted for varying studies of the energy sector. The electricity grid model is calibrated and adopted for the SURE project and will also be complemented by a dedicated gas grid model (see the subsequent section).

While the main model coupling in the subesequent workpackage 6.2 concerns the energy system model STEM, the grid model can be adopted to be integrated with other models withing SURE. For the subesequent workpackage 6.3, the model will be extended to compute security indicators (loading distribution, N-1 analysis).

4.2.2 ATC-Calculation

Switzerland is currently not part of the flow-based market coupling (FBMC) providing an efficient grid representation in the the day-ahead electricity market. Instead, Switzerland has to rely on the more conservative „Available Transfer Capacity“ATC-coupling, putting a global bound on trades with Switzerland that holds regardless of the grid condition. ATC coupling takes place between Switzerland and its four neighboring zones:

- `'CH00'-'FR00'`
- `'CH00'-'DE00'`
- `'CH00'-'AT00'`
- `'CH00'-'ITN1'`

As an initial scenario, the ATC values for Switzerland are based on the values provided in ENTSO-E’s TYNDP. However, a computational tool developed at ETHZ-FEN as part of the Flexible Economic Optimization Framework (FlexECO) modeling suite will compute alternative ATC-values, based on different cooperation scenarios. This could represent a positive shock scenario (if Switzerland would be allowed to join the FBMC) or a negative shock scenario (if the cooperation level between Switzerland and the EU is further reduced).

A detailed documentation will be provided in the report on security investigations, but in a nutshell the ATCs depend on how strongly Switzerland can impact the flows on the neighbouring European transmission lines.

4.3 Export for SURE model coupling

The zonal PTDF-matrix, the vectors of (16) and the ATC values are exported in CSV-Form to perform the model coupling with the STEM model.

The system parameters change during the model coupling in WP6.2, resulting in different export files. Reasons for such changes may include:

- Changes of the overall generator fleet between scenario years
- Seasonal changes in generator availability
- Changes in grid components (e.g., new lines) as investment decision to overcome specific congestions during the energy system planning. This will most likely involve manual iterations with the grid model.

4.4 Additional applications

4.4.1 AC power flow and Multi-period optimization

As described, the transmission grid model outlined above uses a DC-power flow model. This model neglects voltage limits and reactive powers in the electricity grid.

For long-term energy system planning, this approximation is acceptable. As a key advantage, these models can be also used for multi-period optimizations (used for hydro storage scheduling in the base case computation).

However, volatile power injections from renewables and a generally high system load can also lead to reactive power and voltage problems in the transmission grid. These can not be investigated with a DC power flow model, but require the so-called AC power flow model, using a more complex nonlinear power system model.

Depending on the security indicators selected for WP6.3, further advanced modeling tools are available for the SURE project, to perform multi-period simulations and optimizations of AC-power flow models [8].

4.4.2 Distribution grid models

The grid modeling tools developed in this section can be equally applied to distribution grids. While the main assessment in SURE focuses on the national energy model and therefore the transmission grid, several case studies in SURE perform investigations at the distribution grid level.

If needed, the tools and models are readily available for transfer to the distribution grid level [5]. In such cases, network parameters can be provided for detailed modeling or aggregated information, such as annual demand, share of PV and Electric Vehicle (EV) charging stations, can be used to generate synthetic networks. For instance, Figure 5 shows a Swiss residential grid (network level 5 to 7) with high penetration of PV and charging stations, causing high peak loads both during noon (for export of PV) and in the evening (for loads and charging the EVs). Using the grid modeling tools and additional optimization tools for the use of flexibilities, the potential congestions can be identified and mitigated.

These tools will be adopted as needed for other work packages in SURE.

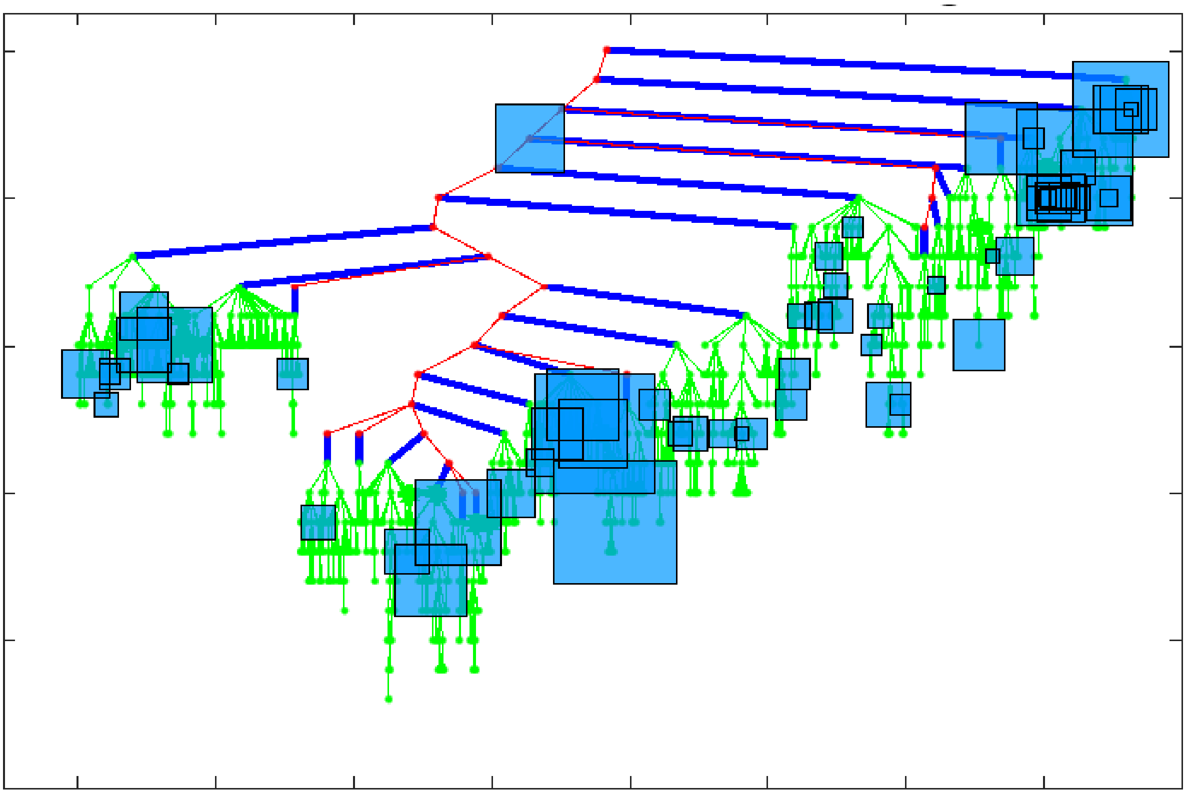


Figure 5: Schematic of a Swiss residential grid (network level 5 to 7) with high penetration of PV and charging stations.

5 Gas grid modeling

This section describes the development of the gas grid model used in SURE project. The main output is a simulation model that allows to investigate the technical capabilities and limits of the gas network.

5.1 European and Swiss grid model data

The modeling of the European gas Grid for SURE uses the following main data sources:

- A public model of the European Network of Transmission System Operators for Gas (ENTSO-G) network, called SciGrid [2]. The data is based on the ENTSO-G grid map and other public sources. The topology is shown in Figure 6 It includes the location and parameters of pipes, nodes, border points, compressors, storages. In particular the essential simulation parameter (length, diameter and capacities of pipes) are taken from this data set.
- The monthly time series for gas trades at all European border points, published by IEA [7]. The time series include the demand, import and export at each border point. A key step in preparation of the European simulation model is, to match the IEA time series to the SciGrid data set. This steps contained some caveats in particular with border points corresponding to villages on each side of the border with names in different languages.
- For many countries, a representative gas demand is included in the SciGrid model, yielding a regional distribution within the country. Additionally, one can infer the total gas demand in a country by computing the import/export balance of the corresponding border points. However, for Switzerland no gas demand data is included in the SciGrid model. Therefore, the data has been complemented by the annual VSG Jahrestatistik [13], which provides the annual total consumption of each canton and can be mapped to the SciGrid model. In addition, the demand data has been scaled to monthly values using typical seasonal distribution of European countries.

As a plausibility check, the SciGrid Data has been compared to public network illustrations, in particular the ENTSO-G grid map (Figure 7) and a schematic of the Swiss gas transmission grid from Gazenergie (Figure 8). All main connections of the SciGrid dataset are also contained in those schematics. However, in the IEA time series some border points are currently not in use, notably the northern border point in Thayngen to Germany and the the eastern border points towards Austria. Therefore, flow variation are performed using the following border points:

- Three border points in the North to Germany and France (Oltingue, Basel, Wallbach)

- One border point in the east to France (Jura)
- One border point in the south to Italy (Griespass)

Further plausibility checks performed on the European system model are outlined in [6].

During the coupling between E-Grid and STEM, demand from potential gas turbines and production / injection from Swiss biogas production and Power-To-Gas units will be added to the model.

5.2 Grid modeling

The nomenclature for the gas grid modeling is provided in Table 2.

The standard flow equations for gas networks are derived from the literature, for instance [11]. The SURE gas grid simulation uses 1-dimensional steady-state flow equations for non-ideal gases.

The main equation for a pipe connecting two nodes i and j is

$$m_{ij}|m_{ij}| = \beta_{ij}(p_i^2 - p_j^2) \tag{18}$$

relating the massflow $\dot{m}_{ij}$ (in kg/s) to the nodal pressures p_i and p_j (in Pa). The coupling parameters

$$\beta_{ij} = \frac{\pi^2 \cdot d^5}{16\lambda \cdot L \cdot R \cdot T} \tag{19}$$

consist of the square of the cross section and additional parameters, namelis the hydraulic resistance factor λ (unitless), the over compressibility factor Z (unitless), the specific gas constant (in J/(kg·K)) the pipe's temperature T (in K), the length of the line L (in m) and the diameter of the line d (in m).

The obvious nonlinearity in (18) comes from the left-hand-side, that square the massflow value, but maintains the sign of the flow direction. The model uses average values for the parameters λ and Z. A more complex model involves additional equations, that express λ as a function of mass flow and pressure and Z as a function of pressure. It has been found that approximations through linearization are not suitable for transmission grids with longer pipeline distances and therefore higher pressure drops [6]. Therefore, the modeling in E-Grid will use the nonlinear gas flow equations.

Besides the equations (18) for each pipe, the network model consists of the nodal balance equation

$$\mathbf{E}_{\mathrm{m}}\mathbf{m} = \mathbf{b} \tag{20}$$

where $\mathbf{m}$ denotes the vector of massflows into the n_{p} pipes and one additional injection from a virtual pipe at the slack node of the system (usually a large import node). $\mathbf{b}$ denotes the vector of injections into the n_{n} nodes (e.g., gas demands, imports, exports, injections from storages). and

The pipe incidence-matrix $\mathbf{E}_{\mathrm{m}}$ is a $n_{\mathrm{n}} \times n_{\mathrm{p}}$ matrix and denotes, which pipe belongs to which node. The entries of the matrix in row i and column j are 1/-1 if pipe

Figure 6: SciGrid representation of the ENTSO-G grid topology.

Table 2: Nomenclature for the gas grid modeling

Symbol	Description	unit
$\mathbf{b}$	vector of injections	kg/s
β_{ij}	Coupling factor pressure to gasflow i	Pa
$\mathbf{E}_{\mathrm{m}}$	pipe incidence-matrix	1
$\mathbf{e}_{\mathrm{s}}$	Slack node incidence vector	1
L	pipe length	m
λ	hydraulic resistance	1
$\mathbf{m}$	vector of massflows	kg/s
m_{s}	Slack node injection	kg/s
$\mathbf{J}$	Jacobian matrix	1
m_{ij}	gas flow from node i to j	kg/s
n_{p}	number of pipes	1
n_{n}	number of nodes	1
$\mathbf{p}^2$	vector of pressures	Pa
p_i	Pressure at node i	Pa
p_{ref}	reference pressure	Pa
R	specific gas constant	J/(kg·K)
$\mathbf{x}$	state vector of Newthon-Rhapson solver	various
Z	over compressibility factor	1

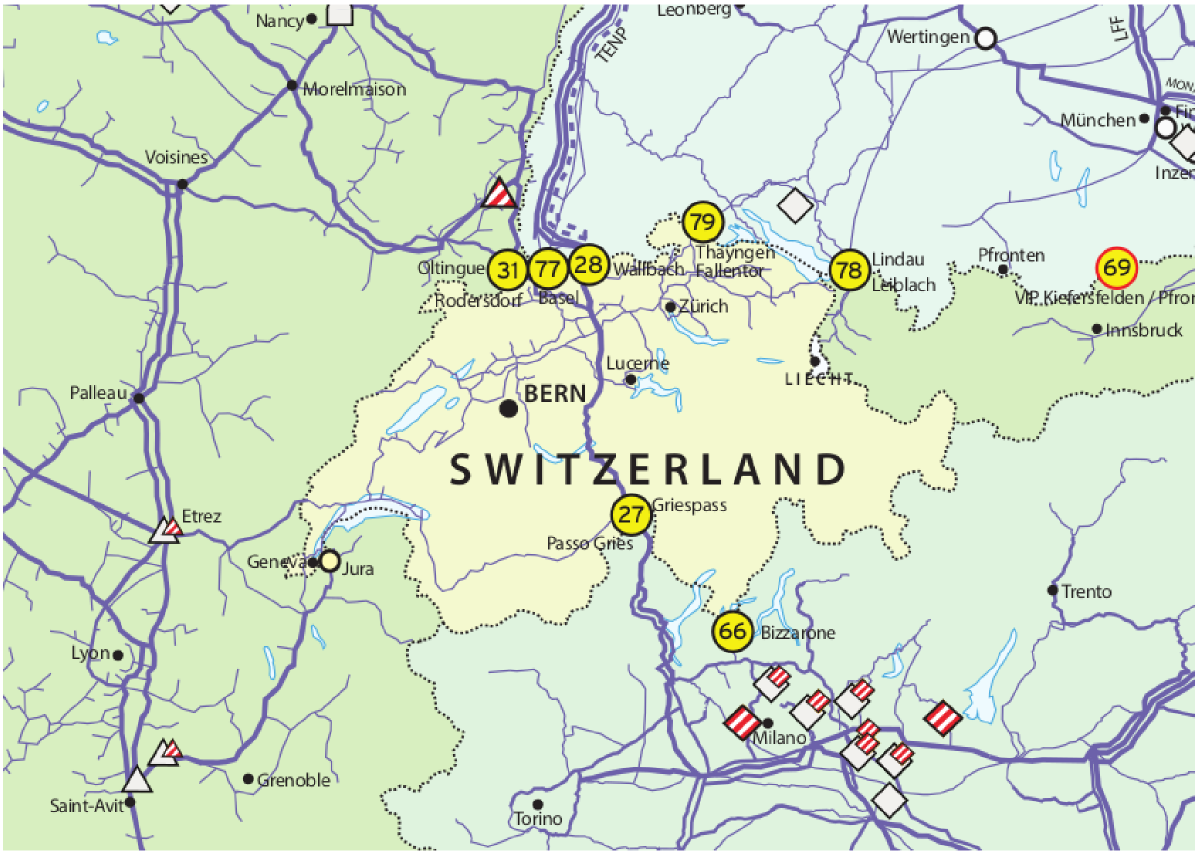


Figure 7: Section of the ENTSO-G grid map surrounding Switzerland. *Source: entsog.eu*

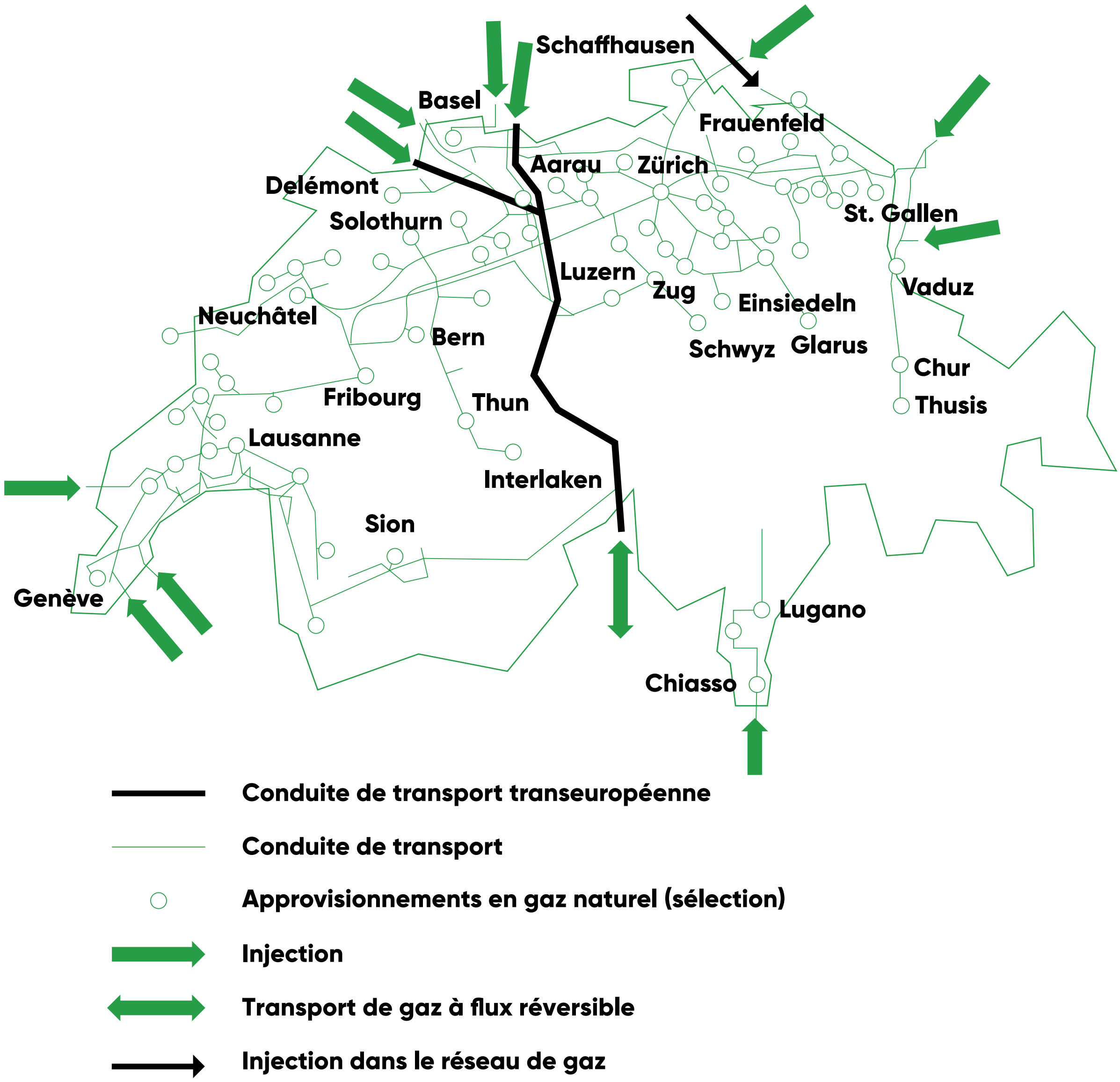


Figure 8: Schematic of the main gas network of Switzerland. *Source: gazenergie.ch*

j is defined leading away from /towards the node i, otherwise the entries are 0. Additionally, the slack nodes has a pressure reference

$$p_{\text{slack}} = p_{\text{ref}} \tag{21}$$

Using vector of massflows $\mathbf{m}$, the vector of the squared pressures $\mathbf{p}^2$ and the slack massflow as variables, one obtains the system of equation

$$\begin{aligned} \mathbf{E}_{\text{m}}\mathbf{m} + \mathbf{e}_{\text{s}} m_{\text{s}} &= \mathbf{b} && (22)\\ \mathbf{E}_{\text{m}}^T \mathbf{p}^2 - \beta \mathbf{m}|\mathbf{m}| &= \mathbf{0} && (23)\\ \mathbf{e}_{\text{s}}^T \mathbf{p}^2 &= -p_{\text{ref}}^2 && (24) \end{aligned}$$

The slack vector $\mathbf{e}_{\text{s}}$ is a vector of length n_{n} with a -1 at the location of the slack node. The vector β consists of the individual factors β_{ij} from the different pipes.
The nonlinear system of equation (24) is quadratic, with the same number of equations and unknowns. It is solved with a dedicated Newton-Rhapson solver implemented in Python, that can efficiently solve also larger gas networks. To this end, the solver needs to repeatedly solve a linear system

$$\mathbf{J}\Delta\mathbf{x} = \mathbf{e} \tag{25}$$

with the $\Delta\mathbf{x}$ denoting at each iteration the update steps of the state vector $\mathbf{x}$,

$$\mathbf{x} = \begin{pmatrix} \mathbf{p}^2 \\ \mathbf{m} \\ m_{\text{s}} \end{pmatrix} \tag{26}$$

the Jacobian

$$\mathbf{J} = \begin{pmatrix} 0 & \mathbf{E}_{\text{m}} & \mathbf{e}_{\text{s}} \\ \mathbf{E}_{\text{m}}^T & -2\text{diag}(\beta|\mathbf{m}|) & 0 \\ \mathbf{e}_{\text{s}}^T & 0 & 0 \end{pmatrix} \tag{27}$$

and the error vector of the nonlinear equation (24)

$$\mathbf{e} = \begin{pmatrix} \mathbf{E}_{\text{m}}\mathbf{m} + \mathbf{e}_{\text{s}} m_{\text{s}} - \mathbf{b} \\ \mathbf{E}_{\text{m}}^T \mathbf{p}^2 - \beta \mathbf{m}|\mathbf{m}| \\ \mathbf{e}_{\text{s}}^T \mathbf{p}^2 + p_{\text{ref}}^2 \end{pmatrix} . \tag{28}$$

To improve convergence and speed up the solution, some parameters of the standard Newton-Rhapson method are modified:

- The solver exploits the symmetric structure of the Jacobian (27).
- The solver modifies the Jacobian for small values of $\mathbf{m}$ to avoid singularities. This occurs only for pipes with no flow, for instances pipe segements in radial grid carrying no gas demand.

- The vector x, the system equations (24) and the linear system with the Jacobian (27) are normalized to typical values, in order to avoid the multiplication of extremely large (pressure square in Pa) and extremely small number (β_{ij} in SI units)

The equations in this section describe the basic gas network equation. Additional equations will be added to include compressors without significantly altering the system structure. Gas storage components can be included at individual time instances as fixed negative or positive injections, representing charging and discharging of the storage. This is further elaborated in an ongoing gas storage study with GAZNAT, related to the SURE project. A storage model can also be use to represent the Linepack effect and will be implemented as part of the gas grid security investigation (WP6.3). In summary, the model allows the robust and efficient solution of transmission gas networks in varying operating conditions. If needed, for coupling with the STEM model or regional SURE case studies, the gas grid model can also be incorporated in more general nonlinear optimization frameworks and software packages.

5.3 Simulations

The key information of the gas grid model that is of interest for the other SURE work packages concerns the technical limitations arising from the gas grid under varying operation conditions, stresses and development paths.

Since a direct coupling of the model with STEM, like for the electricity grid model, is not possible, a different approach is taken. To this end, the gas grid model precomputes maximum and minimum import bounds for each of the border points as well as combined imports/exports and transit flows through multiple border points. Additionally, the model is used to assess stress scenarios like increase transit flows and outages.

The Swiss gas transmission grid in the model has 3 main import directions (North, South, West), 1 main north-south-pipeline, 1 large „triangle loop“(between north, south and west) and a radial grid in the North-East towards Zurich. While the exact European flow conditions and stress scenarios are to be defined in the subsequent task WP6.2 (model coupling) and WP6.3 (computation of indicators), a representative analysis is carried out for testing purposes, that also reflects the recent shocks in the European gas supply.

The variations include

- A change of flow scenarios (import 100 kg/s gas from North, the South or the West)
- A change of transit flows (simulate the model with and without transit flows through Switzerland towards the North)
- The simulation of pipeline losses (for illustration, the pipeline between the South and the West is removed)

- The addition of a large-scale storage (located in Oberwald at the prospective site of a new Swiss gas storage unit)

Future variations will also include injections from domestig gas production (biogas and Power-to-gas).
Figure 9 shows the base loading for different import directions. The figure is part of a webbrowser-based visualization tool, that has been developed for the gas network simulations. In the bottom figure, it can be seen, that some parts of the network are higher loaded depending on the import direction.
Figure 10 illustrates, what happens during an outage scenario. After the loss of the South-West pipeline, the gas flow is shifted north and increases the loading (see in particular pipelines 11-13).
Finally, Figure 11 shows what happens in the case when a storage is added to the model. The gas pipeline loading is decreased by the additional injection. The effect is even more pronounced for additional transit flows in the system (the bottom part of Figure 11). In this case, the initial loading after the outage is over 100%, but can then be mitigated through the activation of the storage unit.

5.4 Export for SURE model coupling

As stated before, the goal of this workpackage is, to extract the key information of the gas grid model concerning potential limitations for the energy system planning in SURE.
For workpackage 6.2, it is envisioned to determine the set of feasible operating conditions based on variables like Swiss demand in each region/canton, import/export (both amount and direction).
During the model coupling, the envisioned and potential future gas flow scenarios will also be validated with European flow scenarios. Furthermore, a plausibility check is being carried out with the industry partners of SURE and related projects.

5.5 Additional applications

Future applications of the developed gas model include both the SURE and FlexECO modeling framework [4]:

- Execution of additional storage investigations to characterize the value of flexibility in the gas network,
- assessment of sector coupling approaches combining the utilization of the electricity system, the gas system as well as assessments of the role of synthetic fuels,
- related to the previous point, the assessment of the impact of gas turbines on the flow situation in the gas network.

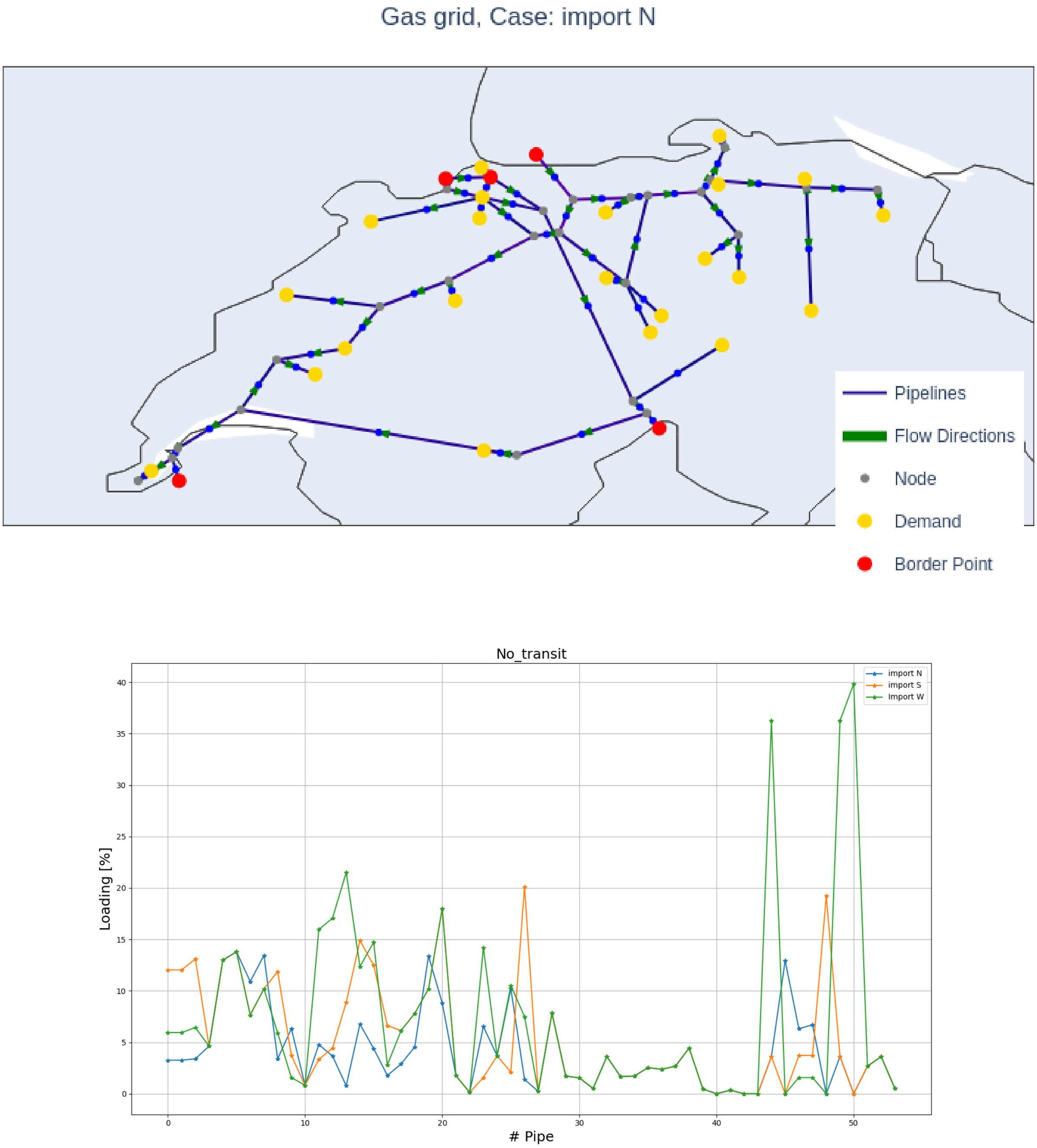


Figure 9: Top: Illustration of the modeled Swiss transmission grid with import points (red), demand nodes (yellow) and 54 pipelines.
Bottom: Loading of the 54 pipelines when about 100 kg/s gas demand is served from different import directions.

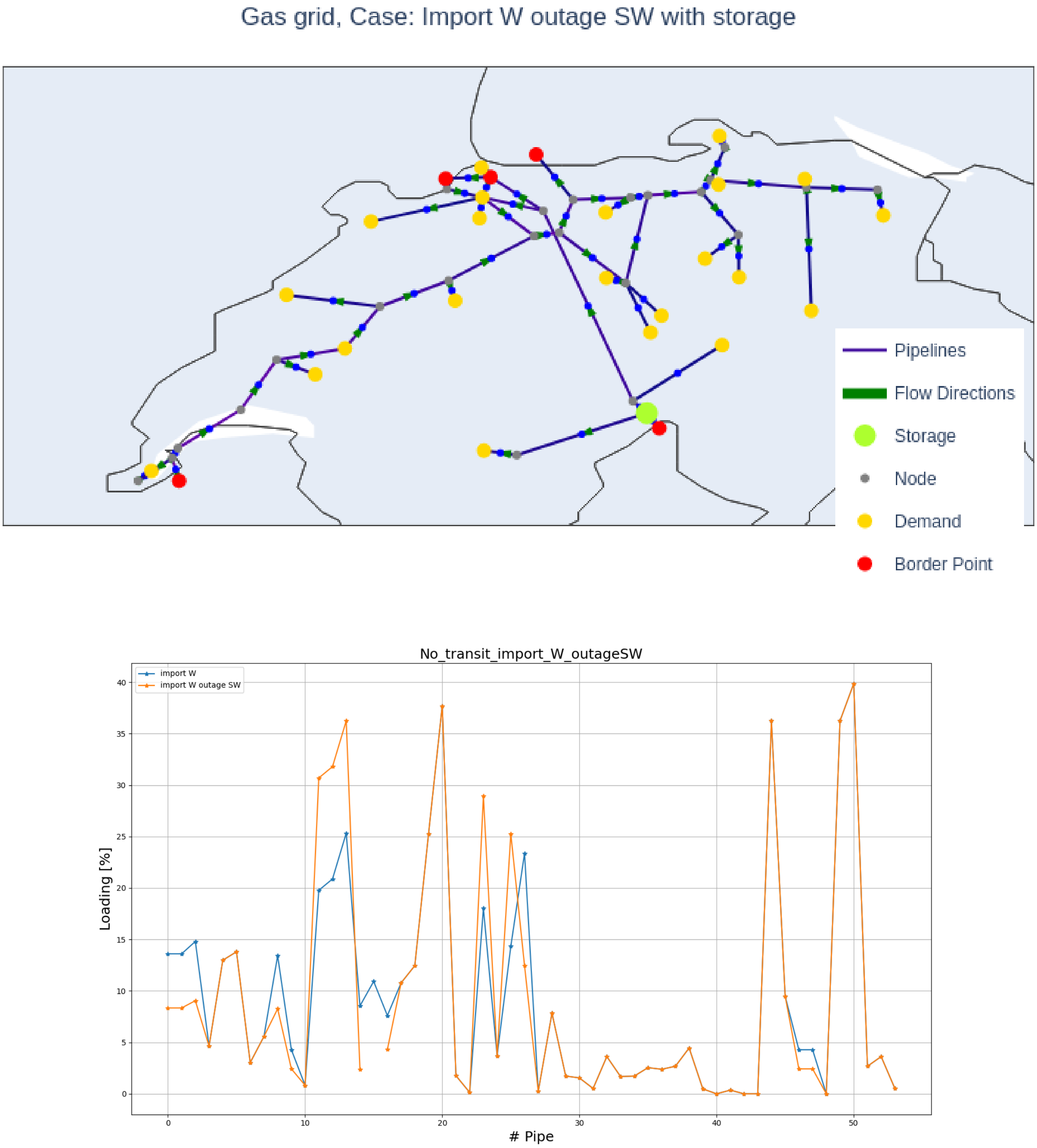
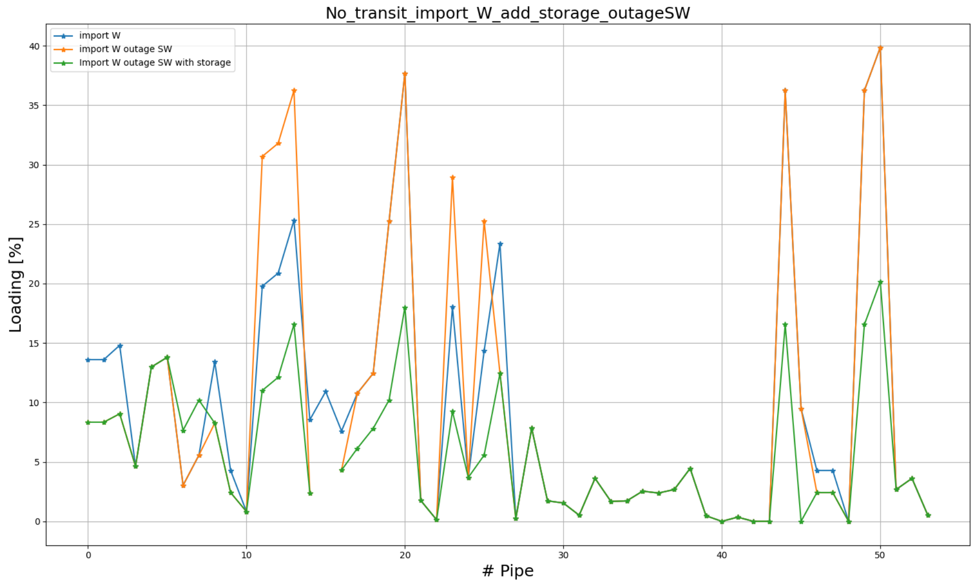


Figure 10: Top: Illustration of the modeled Swiss transmission with the South-West pipeline lost.
Bottom: Loading of the 54 pipelines when about 100 kg/s gas demand is served from the West and with and without the outage.



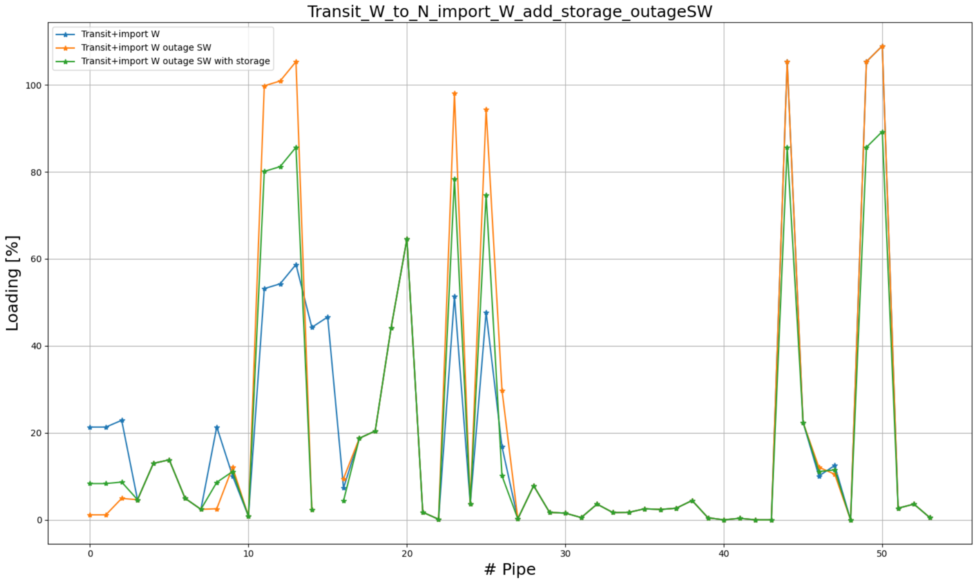


Figure 11: Top: Loading of the 54 pipelines when about 100 kg/s gas are served from the West, with an outage and an additional storage injecting 50 kg/s.
Bottom: Loading of the 54 pipelines when about 100 kg/s gas and 175 kg/s of export to the North are served from the West, with an outage and an additional storage injecting 50 kg/s.

The selection of the additional applications within SURE will depend on the selected development paths as well as stress / shock scenarios (see the SURE-deliverable D2.1 for further details).

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