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SURE

D 6.2
Report on energy grid coupling

Developed by

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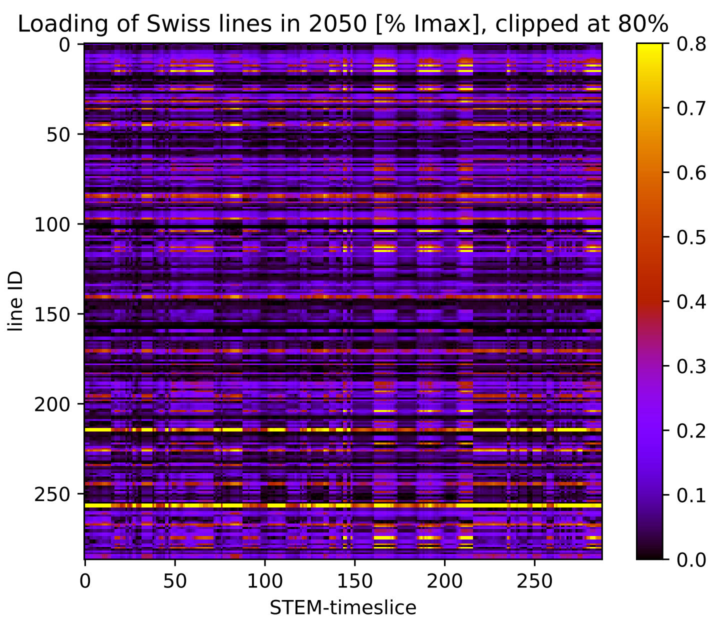
Research Center for Energy Networks (ETHZ)



Zurich, February 16, 2024

1 Executive summary

This deliverable describes the energy grid model couplings between the FlexECO grid models of ETHZ with other models used within the SURE framework.
The main model couplings take place between the FlexECO models for electricity and gas grids with the STEM energy system model (PSI-EEG, WP7). On the electricity grid side, a hard coupling is performed with simplified transmission grid constraints. For the indicator computation, STEM time series are regionalised in the FlexECO model in order to perform a detailed grid security computation. The underlying electricity grid model includes the full Swiss transmission grid. The European transmission grid, used to model imports from neighboring countries into Switzerland, is represented in an aggregated manner, but derived from a detailed European transmission grid model.
On the gas grid side, simplified transmission grid constraints are provided to STEM through the available border point capacities, also accounting for the preloading of the network through transit gas flows. During the preparation of the indicator computation, a review of operational challenges from literature and discussion with Swiss gas grid operators has identified the need for a higher spatial and temporal granularity of the gas grid simulator than the simple static modeling approach described in the previous deliverable. The newly developed dynamic Swiss gas grid simulator can assess the remaining security margins during pressure shocks after unscheduled demand changes, for instance from gas power plants.
Further model couplings include the coupling with the EXPANSE tool (Uni Geneva, WP5) . It is similar to the electricity grid coupling with STEM, but has a different temporal and spatial resolution, with a particular focus on the installation of PV.
In addition, the FlexECO grid planning tools will be coupled with the Building Stock model (TEP Energy, WP14) for the case study specific heat grid planning. This coupling is under development within WP14.
Finally, FlexECO is formally coupled with the multi criteria decision analysis (PSI-TAG, WP1) to provide the computed grid security indicators in the appropriate format for further processing.

2 Zusammenfassung

Dieser Bericht beschreibt die Kopplung der FlexECO-Netzmodelle der ETHZ mit anderen Modellen die im Rahmen des SURE-Projekts verwendeten werden. Die wichtigsten Modellkopplungen finden statt zwischen dem FlexECO-Modell für Strom- und Gasnetzen mit dem Energiesystemmodell STEM (PSI-EEG, WP7). Auf der Seite des Elektrizitätsnetzes Seite wird eine harte Kopplung mit vereinfachten Übertragungsnetzbeschränkungen durchgeführt. Für Indikatorberechnung werden die STEM-Zeitreihen im FlexECO-Modell regionalisiert, um eine detaillierte Netzsicherheitsberechnung durchführen zu können. Das zugrunde liegende Stromnetzmodell umfasst das gesamte Schweizer Übertragungsnetz. Zur Abbildung der Einspeisung aus benachbarten Ländern wird das europäische Netz in aggregierter Form dargestellt, ist aber aus einem detaillierten europäischen Übertragungsnetzmodell abgeleitet. Auf der Seite des Gasnetzes werden vereinfachte Übertragungsnetzbeschränkungen für STEM durch die verfügbaren Grenzpunktkapazitäten bereitgestellt, wobei auch die Vorbelastung des Netzes durch Transitflüsse berücksichtigt werden. Während der Vorbereitung der Netzberechnung hat eine Überprüfung der betrieblichen Herausforderungen anhand der Literatur und durch Diskussionen mit Schweizer Gasnetzbetreibern ergeben, dass eine höhere räumliche und zeitliche Granularität des Gasnetzsimulators benötigt werden, als der einfache statische Modellierungsansatz der im letzten Deliverable beschrieben wurde. Der neu entwickelte dynamische Schweizer Gasnetzsimulator kann die verbleibenden Sicherheitsmargen des Gasdrucks nach ungeplanten Nachfrageänderungen von Gaskraftwerken abschätzen.

Zu den weiteren Modellkopplungen gehört die Kopplung mit dem EXPANSE-Tool (Uni Genf, WP5) . Sie ähnelt der Stromnetzkopplung mit STEM, hat aber eine andere zeitliche und räumliche Auflösung, mit einem besonderen Fokus auf die Installation von PV. Darüber hinaus werden die FlexECO-Netzplanungstools mit dem Building Stock Modell (TEP Energy, WP14) für die fallstudienspezifische Wärmenetzplanung gekoppelt.

Schliesslich wird FlexECO formell mit der multikriteriellen Entscheidungsanalyse gekoppelt (PSI-TAG, WP1), um die berechneten Netzsicherheitsindikatoren in einem geeigneten Format zur Weiterverarbeitung bereitzustellen.

3 Summary of coupling with SURE partners

While the previous deliverable D6.1 [1] focused on the modeling aspects for electricity and gas grids, this deliverable focuses on the model couplings with other SURE models and an initial indicator computation. The subsequent deliverable D6.3 will focus in more detail on the security and resiliency indicators.
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. The previous deliverable D6.1 [1] summarized the interactions with SURE partners that led to the following model couplings presented in this deliverable:

- The coupling of the **FlexECO electricity grid model with STEM** (PSI-EEG, WP7) is presented in Section 4. It is the first main model coupling and involves a bi-directional coupling. From FlexECO to STEM, a hard coupling is performed with simplified transmission grid constraints. From STEM to FlexECO, a soft coupling is performed through the exchange of simulation results for the computation of grid security indicators, using a broad range of detailed electricity grid analysis.
- The coupling of the **FlexECO gas grid model with STEM** (PSI-EEG, WP7) is presented in Section 5. It is the second main model coupling and involves a bi-directional coupling. From FlexECO to STEM, a hard coupling is performed with simplified transmission grid representation through the available border point capacities. From STEM to FlexECO, a soft coupling is performed through the exchange of simulation results for the computation of grid security indicators, using a dynamic gas grid simulations to identify the robustness of the gas grid to demand variations.
- The coupling of the **FlexECO electricity grid model with EXPANSE** (Uni Geneva, WP5) is presented in Section 6.1. It is similar to the electricity grid coupling with STEM, but has a different temporal and spatial resolution. The goal is to directly compute grid security indicators for EXPANSE simulation results, as an addition to the coupling that is intended between EXPANSE and STEM.
- The coupling of the **FlexECO electricity grid model with the Building Stock Model** (TEP Energy, WP14) is a **case study specific coupling**. The goal is to perform a heat grid planning computation using the example of the city of Zurich. It is presented in Section 6.2.
- The coupling of the **FlexECO Grid models with the SURE-MCDA** (multi criteria decision analysis, PSI-TAG, WP1) is a formal coupling. The goal is to provide the computed grid security indicators in the appropriate format for further processing as input to the multi criteria decision analysis. It is presented in Section 6.3.

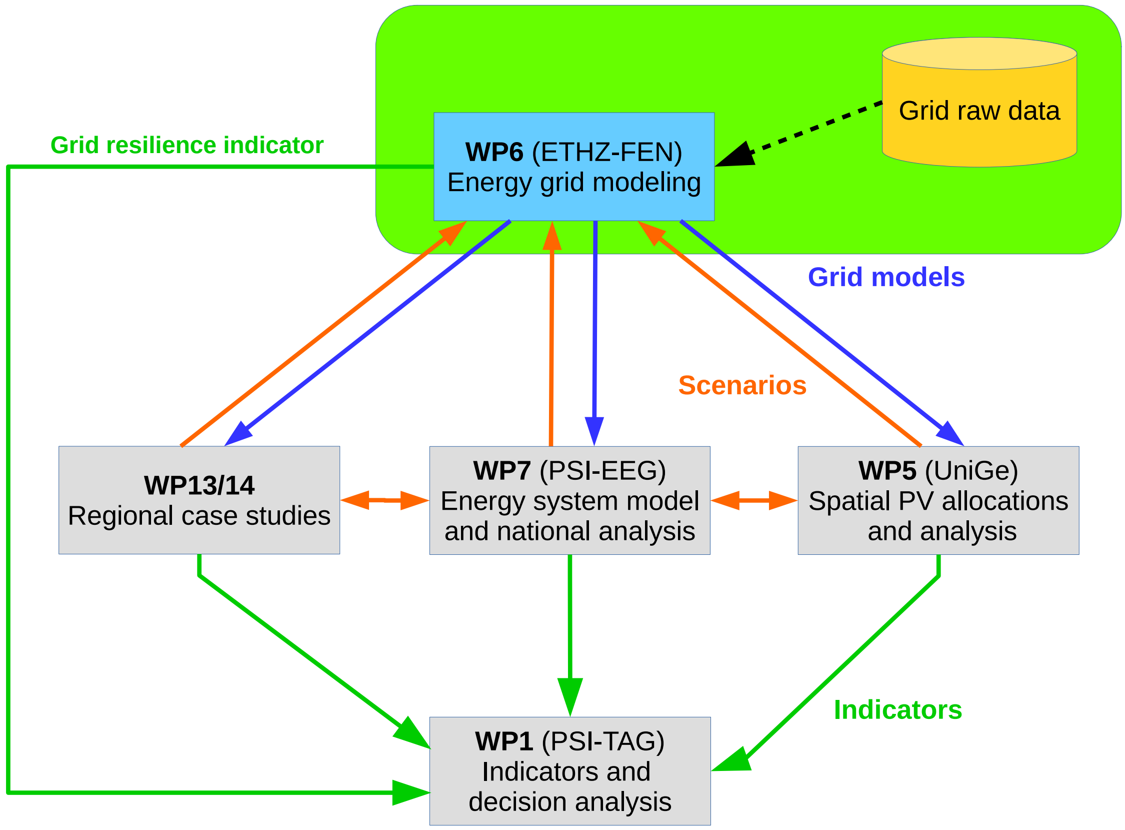


Figure 1: Interaction of WP6 with SURE partners from other work packages. The interactions include energy grid models, calibration scenarios and indicators.

4 Electricity grid coupling with STEM (PSI-EEG)

The general method for electricity grid modeling has been outlined in the SWEET-SURE deliverable 6.1 [1]. This section describes, how the bidirectional coupling with the STEM energy system has been achieved.

4.1 FlexECO to STEM

The coupling from FlexECO grid model to the STEM energy system model is a hard model coupling. As outlined in section 3 of [1], STEM performs an energy system optimization, that required an adequate representation of the electrical transmission grid and its constraints for national and international power exchanges. Rather than exchanging the data for network limitations at each model iteration, either through a manual or automated process, a grid model is incorporated in the STEM energy system model, to be taken into account at each iteration of the model execution.
To this end, a simplified representation of the electricity grid model is developed. We first outline the model description and then discuss its limitations.

4.1.1 Description of the grid model for integration in STEM

The model basis is a detailed nodal description of the European transmission grid model. Recall from [1] the linear power flow formulation

$$\mathbf{f} = \mathrm{M}_\mathrm{n}\mathbf{p}_\mathrm{n} \tag{1}$$

$$-\mathbf{f}_\mathrm{max} \leq \mathbf{f} \leq \mathbf{f}_\mathrm{max} \tag{2}$$

with the vector of line flows $\mathbf{f}$, the vector of maximum line flows $\mathbf{f}_\mathrm{max}$, the vector of nodal power injections $\mathbf{p}_\mathrm{n}$, and the nodal PTDF-matrix M_n coupling the two vectors. In the detailed European model, there are $n_\mathrm{l} = 5423$ line flows (transmission lines or transformers) and $n_\mathrm{n} = 3690$ nodes.
For the investigations in SWEET-SURE, only a part of this model is of interest, by selecting and aggregating the nodal model in (1). First, only the Swiss transmission lines, including the cross border lines, are considered, by selecting only the corresponding elements of the vector $\mathbf{f}$ and the rows of the PTDF-maxtrix M_n. In total, this leaves 287 line flows. Secondly, the nodes of the model are aggregated according to the representation in the STEM energy system model, by computing the nodal injections from an aggregated zonal representation:

$$\mathbf{p}_\mathrm{n} = \sum_{i}^{n_\mathrm{z}} \mathbf{g}_i \cdot p_{\mathrm{z},i} = \mathbf{G} \cdot \mathbf{p}_\mathrm{z} \tag{3}$$

Instead of $n_\mathrm{n} = 3690$ nodes with independent injections, the electricity flows are defined by $n_\mathrm{z} = 25$ independent power injections variables $p_{\mathrm{z},i}$. These variables are distributed to the nodes through the mapping vectors $\mathbf{g}_i$, each of which has $n_\mathrm{n} = 3690$ elements and is normalized, so that all entries sum to magnitude 1.

For example, the nominal electricity demand (annual energy) at each node of a given zone is collected at the corresponding entry of the vector $\mathbf{g}_i$, all other entries of the vector are set to zero. Subsequently, the vector is divided by the total sum of the electricity demand in that region, so that the vector becomes normalized and sums to 1. If the vector is now multiplied with different values for the total demand power in the zone, corresponding to different times of the day or the year, the mapping vector distributes this power to each of the nodes.
The mapping vectors form the columns of the mapping matrix $\mathbf{G}$ and the power injection variables are arranged in the aggregated injection vector $\mathbf{p}_z$ [1].
The definitions of the power injection variables are aligned with the STEM model. The 25 variables and the assumptions for the corresponding mapping vectors $\mathbf{g}_i$ are as follows:

- 4 variables model the **imports** from the neighboring market zones around Switzerland (`AT, DE, FR, IT`). The mapping vectors $\mathbf{g}_i$ are the total rated power of the flexible generation in each market zone at the corresponding nodes, normalized to magnitude 1. The entries corresponding to nodes outside the market zone or without flexible generation are set to zero. Since the network data covers a detailed European power grid [2], the model captures how import and export flows are distributed between the cross-border lines. This is important to assess how transit flows and loop flows impact the Swiss transmission grid.

- 4 variables model the **export** to neighboring market zones. The mapping vectors $\mathbf{g}_i$ are the same as for the imports (with opposite sign), since cross-border flows typically lead to an increase or decrease of the flexible generation (as opposed to changes in loads or fixed renewable generation).

- 7 variables model the **load** of the NUTS2 regions of Switzerland (`CH01, CH02, CH03, CH04, CH05, CH06, CH07`). The mapping vectors $\mathbf{g}_i$ are the total currently installed load within each Swiss region at the corresponding nodes, normalized to magnitude 1. The entries corresponding to nodes outside the region or without load are set to zero.

- 7 variables model the **flexible generation** of the NUTS2 regions of Switzerland. The mapping vectors $\mathbf{g}_i$ are the total currently installed flexible generation capacity, normalized to magnitude 1. The entries corresponding to nodes outside the region or without load are set to zero. Almost all of the flexible generation is comprised by hydro power.

- 3 variables model the **nuclear generation** Switzerland (Beznau, Gösgen, Leibstadt). The mapping vectors $\mathbf{g}_i$ have an entry "1" at the corresponding node, and are zero at all other nodes.

[1] Note that this model structure is similar to the Flow-based market coupling in the ENTSO-E network, where the mapping vectors are the GSKs (generation shift keys) and the injection vector are the zonal net position. Other parts of the aggregated grid model are different, like specific power plant information for nuclear and no base case power flows.

The list is not exhaustive an will be extended as needed to include **additional variables**:

- **Solar**, which is currently modeled as reduction of the load in each NUTS2-region, can be added as one or more regional variables to the model, to refine the modeling detail. The project partners are in exchange with the modeling team of EXPANSE to exchange the solar information with a more refined temporal and spatial resolution. To this end, the solar distribution in EXPANSE, created on municipality level, will be mapped to the transmission grid nodes of the Swiss network model. The coupling with EXPANSE is outlined in Section 6.1, the results will be part of the deliverable D6.3 on indicator analysis.
- **Wind** production in Switzerland is currently too low to provide an adequate distribution vector for future scenarios. In the current modeling, it is distributed uniformly across each NUTS2-regions. However, the spatial distribution will be further refined with the coupling to the EXPANSE model, outlined in Section 6.1.
- The installation of **large new power plants** (for instance during the shock of nuclear reintroduction) will be added as a separate model variable and mapped to a specific node.

Combining equations (1)-(3) results in the aggregated grid model

$$-\mathbf{f}_{\mathrm{max,z}} \leq= \mathbf{M}_{\mathrm{z}}\mathbf{p}_{\mathrm{z}} \leq \mathbf{f}_{\mathrm{max,z}} \tag{4}$$

where $\mathbf{M}_{\mathrm{z}}$ results from the multiplication of the nodal PTDF matrix $\mathbf{M}_{\mathrm{n}}$ with the mapping matrix $\mathbf{G}$ and the selection of the 287 Swiss lines.
The Swiss line flow limits $\mathbf{f}_{\mathrm{max,z}}$ are the corresponding 287 entries of the original limits $\mathbf{f}_{\mathrm{max}}$, scaled by a factor 80%. This scaling represents an operational security margin to serve as a **proxy for N-1 security**, since all lines now have a 20% reserve for the additional loading occurring during outages. A more detailed N-1 analysis will be performed for the security indicator computation in the detailed FlexECO model.
With this model, future changes in generation or load considered can be directly mapped to the detailed model to test, whether they respect the grid constraints (2).

4.1.2 Export and visualization

The Swiss network, the voltage levels and the zonal NUTS2 structure is illustrated in Figure 2. The shown network illustrates the data from [2]. For the numerical study, it is further checked with recent Swissgrid data, including all network upgrades until 2025. The map is an interactive webbrowser-based visualization, that will also serve to illustrate loadings and the impact of shocks in different parts of the network.
The matrix and the vectors of (4) are exported as CSV table, to be read by STEM. Note that this data transfer only needs to occure once for a given network.

In addition, the option of line upgrades is currently under discussion. To this end, a cost estimate for the doubling of a selected lines would need to be selected, allowing STEM to increase the corresponding bounds of (4).

4.1.3 Model reduction procedure

Due to the computational complexity in STEM, in particular regarding memory, it is of interest to reduce the model size of the network constraints. To this end, a minimal representation of the network constraints through the identification of critical lines is performed as follows.

- To test, if the upper bound of line i is required, solve the following optimization problem:

$$f^* = \max_{\mathbf{p}_\mathrm{z}} \quad \mathbf{m}_{\mathrm{z},i}\mathbf{p}_\mathrm{z} \tag{5}$$

$$\mathbf{p}_{\mathrm{z,min}} \leq \mathbf{p}_\mathrm{z} \leq \mathbf{p}_{\mathrm{z,max}} \tag{6}$$

$$-\tilde{\mathbf{f}}_{\mathrm{max,z,i}} \leq \mathbf{M}_\mathrm{z}\mathbf{p}_\mathrm{z} \leq \tilde{\mathbf{f}}_{\mathrm{max,z,i}} \tag{7}$$

  where $\mathbf{m}_{\mathrm{z},i}$ is the i'th row of the matrix M_z and $\tilde{\mathrm{f}}_{\mathrm{max,z,i}}$ is the same as $\mathrm{f}_{\mathrm{max,z}}$, except of the i'th entry set to a large value. The limit vectors $\mathbf{p}_{\mathrm{z,min}}$ and $\mathbf{p}_{\mathrm{z,max}}$ are estimates how large and how small each of the 25 STEM model variables can become, for example the maximum load in each of the regions. These can be large conservative bounds, to avoid keeping lines that are only limiting in very extreme scenarios.

- If the solution f^* is larger than the original i'th entry of the $\mathrm{f}_{\mathrm{max,z}}$, the line constraint will be limiting and should be kept. Otherwise, it is redundant.

- The procedure is repeated for the lower line limit, only as a minimization and comparing to the lower line limit. If both the upper and the lower line limit are redundant, the i'the line constraint can be discarded, since the line will never be limiting.

The procedure is repeated for all 287 lines of the Swiss grid model. In total, it is possible to reduce the grid model to about 67 lines. All other lines can not become limiting under any reasonable injection scenario following the model (4).

4.1.4 Impact of electricity grid model simplifications

This section summarizes the simplifications and assesses their impact on the validity of the indicators, computed both with FlexECO and STEM.
The following simplifications were performed for the **FlexECO grid model**:

- The FlexECO model is a **DC-power flow model** and has no representation of voltages or line losses. Most grid congestions originate from line flow limitations, that are modeled with sufficient accuracy by this model. However, the

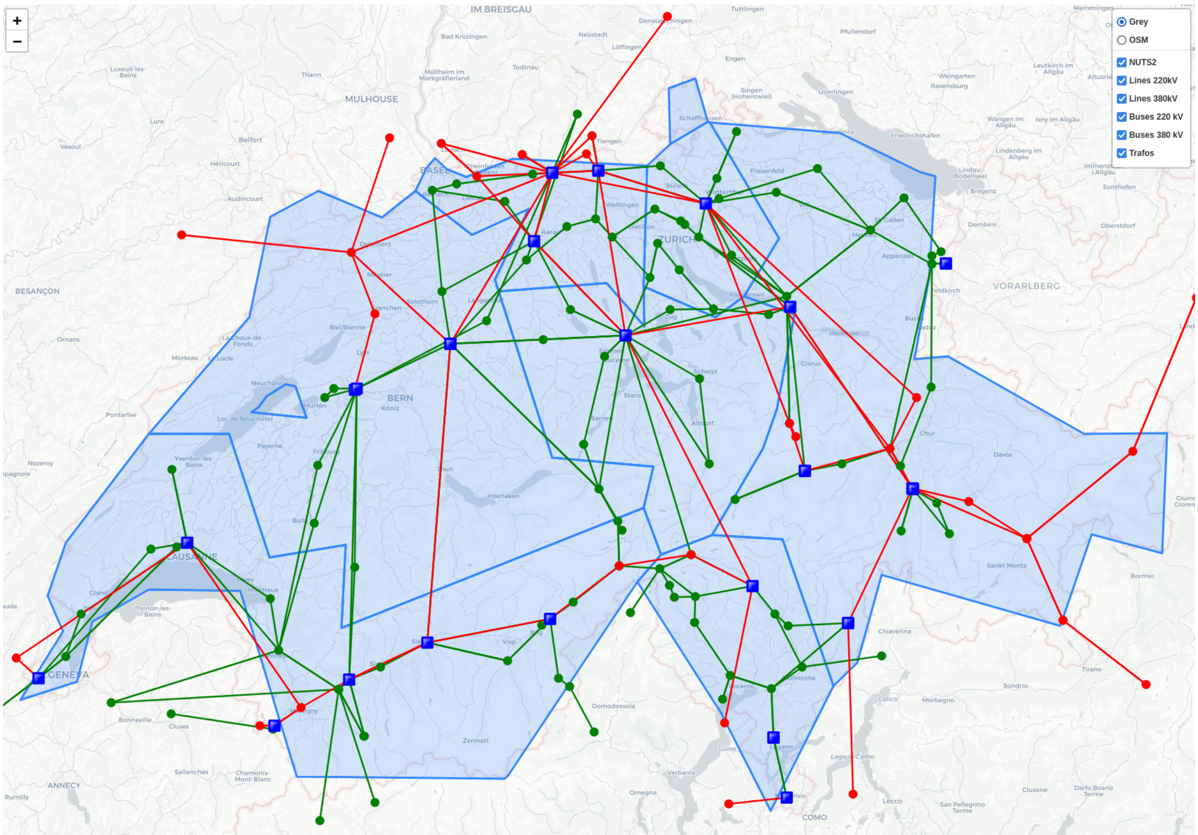


Figure 2: Webbrowser-based illustration of the Swiss transmission grid (based on data from [2]), used for implementation in the STEM model: 287 branch elements (380 kV lines, 220 kV lines, coupling transformer). The network is partitioned into the 7 Swiss NUTS2 statistical regions. Each node has a designated load and generation portfolio used to regionalize the aggregated electricity profiles of the STEM model.

FlexECO model can be in principle also updated to an AC-power flow model by introducing voltage and reactive power variables, as well as making standard assumptions for reactive power demand and line resistances. It is foreseen to perform AC power flow simulations for selected grid conditions during the indicator computation to quantify the accuracy of the grid loading indicators based on the DC power flow model.

- The FlexECO model is based on a **scaling of the Swiss generation and load portfolio** based on today's (2023) values. Future generation units and loads are modeled through the mapping vectors as a scaling of today's capacities, maintaining the relative distribution within each region. In reality, both the load distribution and the generator power can fluctuate within the regions, leading to congestions that are overlooked with a simple scaling. To address this issue, it is foreseen to compute power grid indicators based on randomized variations of the power distribution within each region. Preliminary analysis indicates that the scaling approach underestimates the peak line loads by about 10%, depending on the size of the variation. For new investments of specific large power plants, such as the shock scenario of nuclear reintroduction, manual adjustments with dedicated new variables are foreseen.

The following additional simplification were performed for the **STEM grid model**:

- The STEM model operates with **representative time slices of the average power injection** over a period between 13 and 65 hours of different days within a season. In reality, power injections fluctuate around this average, causing higher loading of the power grid. To address this issue, an additional margin is applied to the line flow limits (currently 80% for the combined margin for N-1 security and power uncertainty). Additionally, the detailed FlexECO model will perform a statistical randomized variation to compute a robust grid security indicator of each STEM scenario.

- The **model reduction procedure** outlined in Section 4.1.3 is only a reduction of the model size, not its accuracy. The method identifies redundant line limits, that can never become constraining for the model. As illustrative example, consider two line segements connected in series, one having a smaller current limit than the other. The line segment with the smaller limit will always become constraining before the line segement with the higher limit, which can therefore be omitted from the model without loss of accuracy. Note that the impedance and flow through the line is still part of the electricity grid model, since it also affects the flow in the rest of the network. Only the row for the redundant current limit will be removed, which can never become constraining anyhow. Therefore, optimizations with the reduced model within STEM will yield the same results as optimizations with the original model (4).

- The model aggregation into zones for Swiss regions and neighboring countries, outlined in Section 4.1.1, assumes a **zero base case injection** for all zonal variables. For the Swiss variables, which capture *all* productions and loads within Switzerland, this assumption is adequate and will be complemented by variations around the nominal scaled injection, as outlined in the beginning of this section. However, neighboring countries have large internal power transfers between generation and load centers, that also affect Switzerland. The impact of these European power flows will be quantified with the detailed grid security indicator computation. First, **transit power flows** (most notably from the North to Italy) can be modeled by simultaneously increasing and decreasing the power injection of neighboring market zones. Secondly, **loop flows** originate from power exchanges between neighbors (for instance Germany and France), that also partially flow through Switzerland. The loop flow assessment requires additional variables for the non-Swiss loads, that is not part of the STEM model, but will also be integrated in the grid security indicator analysis in FlexECO.

- The grid model provided to STEM captures the **nominal grid security constraints** without a representation of individual line outages. In reality, the Swiss transmission grid is operated under the N-1 security requirement, requiring that the outage of any line or transformer keeps the remaining lines within their flow limits. Investigations with the FlexECO grid model used in this study have led to the simplified criterion of reducing the allowed line loading to 80% of the nominal limit, which is an average value. Some lines may require more or less reduction in actual N-1 simulations. To quantify the grid security margin as an indicator, an actual N-1 simulation will be carried out for all STEM scenarios within the FlexECO grid model.

- **Line flows limits of European lines** are not considered in the modeling for STEM. In practise, these limits are managed by the TSOs of each market zone. Indirectly, the ATC limits for power exchanges between Switzerland and its neighbors help to maintain the grid security. Additionally, Switzerland may be part of international redispatch measures with its neighbors, if necessary to relieve congestions after the market clearing. In SURE, ATC bounds are considered in the STEM model and selected in a conservative manner, to investigate the impact of reduced import bounds. In total, this simplification has only minor impacts on the validity of the SURE simulations.

4.2 STEM to FlexECO

The coupling from STEM to the FlexECO grid model is a soft model coupling. Simulation results of the relevant scenarios are imported by FlexECO and used for the computation of various grid security indicators The procedure and its application is described in the following sections.

4.2.1 Import of STEM results

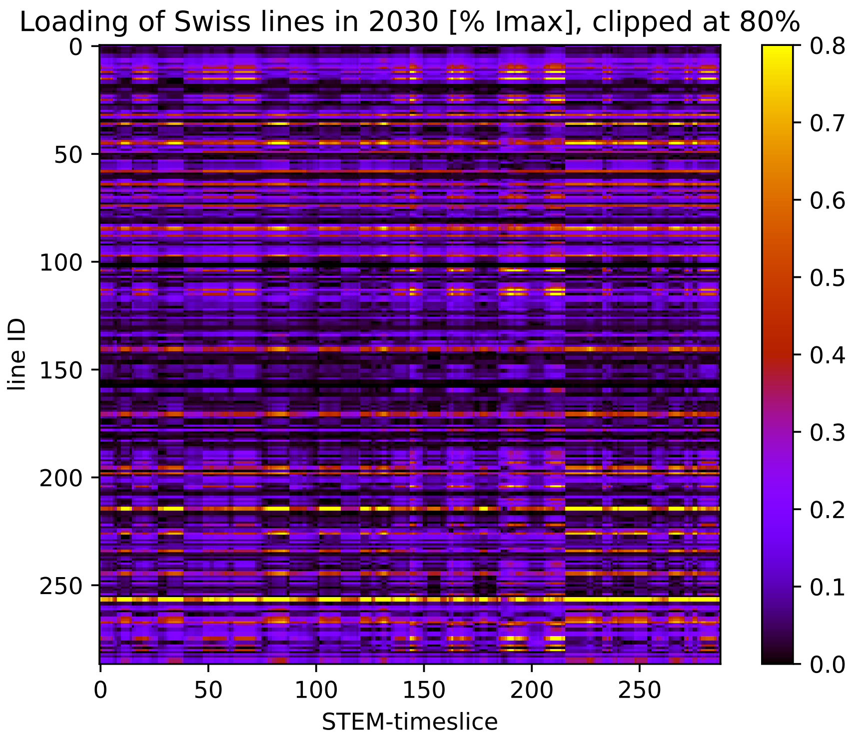
STEM provides for each scenario three sets of results for the scenario years 2030, 2040 and 2050. Each set of results consists of 25 times series, corresponding to the 25 injection variables summarized in Section 4.1.1. The length of each time series is 288 time steps of 12 representative days (4 seasons; 1 weekday, 2 weekend days).
FlexECO uses the Python interface to read the time series, and integrate it with the grid model. It is then applied to perform a grid loading analysis and the computation of various grid security indicators for the SURE indicator database.
Note, that 12 representative days in hourly resolution can be copied and concatenated in appropriate order to obtain a full annual time series of 8760 time steps. However, this time series only captures the **average** load value and is not appropriate for the computation of grid security indicators, since the peak load of a given hour can be much high than the average over the same hour on multiple days. Therefore, a robustness assessment for the spatial and temporal variation will be performed as outlined in Section 4.2.3, including a randomized variation and pattern identification based on historical load data.

4.2.2 Grid loading analysis

This section illustrates the grid loading analysis, that is performed using the FlexECO simulator. Note that the results are preliminary, based on example time series provided by STEM and should not be used for quantitative conclusions. Such conclusions will be drawn with the indicator analysis of the subsequent deliverable (Sure D6.3). This section still shows some quantitative results, to illustrate how the coupling from STEM to FlexECO operates.
Given a combination of scenario and scenario year, FlexECO performs a grid simulation for each of the 288 time steps. The example illustration use the STEM scenario BAU and the three years 2030, 2040 and 2050. The time series were computed before incorporating the STEM grid model, outlined in Section 4.1.1. To illustrate the import and the loading indicators, a simulation of the base loading is performed for each of the 288 time steps. The top plots of figures Figure 3 to Figure 5 illustrate the loading for each combination of line and time step. Yellow sections in the figure indicate combinations of lines and time steps with overloading.
It can be seen that the most overloadings occur at specific lines in the network. To better identify the overloadings, the bottom plots of Figure 3 to Figure 5 show the overloaded lines (at or above the security limit of 80% line capacity). It can be seen, that the number of overloadings increase from 2030 to 2040, but then again decrease from 2040 to 2050.
To better illustrate this result, a first aggregation is performed, summing the total of all line overloadings for each time step, illustrated in Figure 6. It can be seen, that overloadings occur throughout the year, with some hours showing as much as 3 times the overloadings as other hours. In order to compute a scalar grid indicator, the result is further aggregated by summing all overloadings of each scenario year,

illustrated in Figure 7. The plot confirms the observation of a sharp increase in overloadings from 2030 to 2040, followed by a mild decrease in 2050. Note that a full integration of the grid model in FlexECO should resolve all overloadings above 80%. However, the candidate indicator will be complemented with additional grid security indicators outlined in the next section, which perform a simulation of the FlexECO grid model under increased stress through the temporal and spatial variation of the loading distribution.

Additionally, the grid loading analysis will be used to test the impact of potential **Swiss and European grid expansions**. On the one hand, potential grid expansions at an advanced planning state can be incorporated in the grid model data. On the other hand, lines with frequent limitations (yellow markings in Figure 3 to Figure 5) can be identified and reinforced in simulation, both in FlexECO and as update to STEM. This allows to assess the effctiveness of the reinforcement for the grid and supply security indicators.



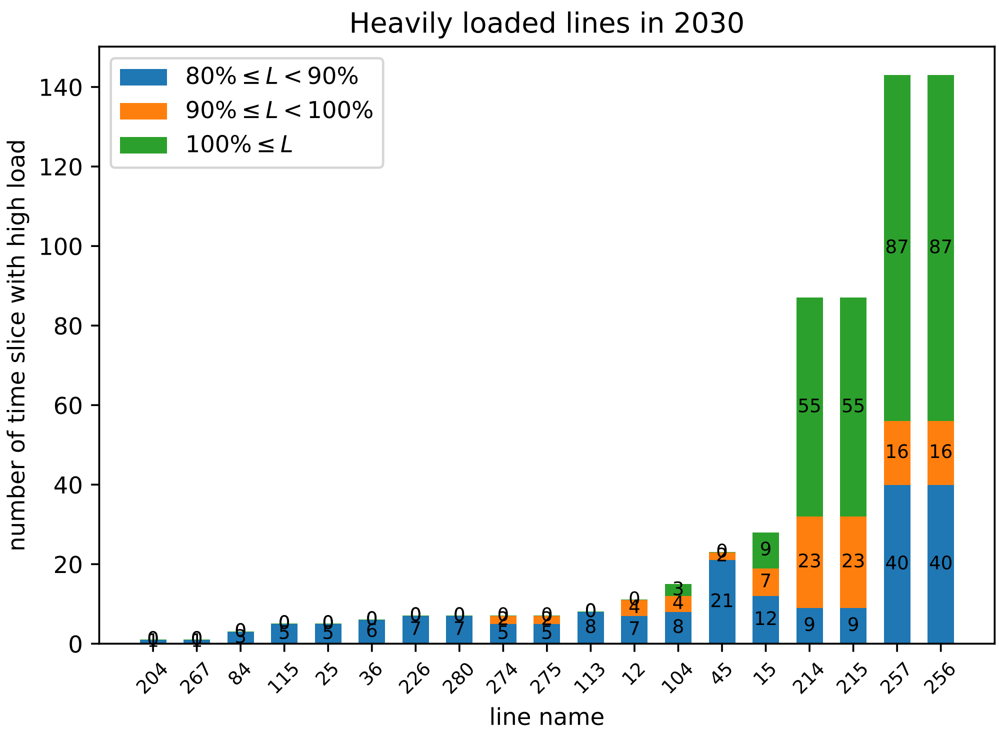
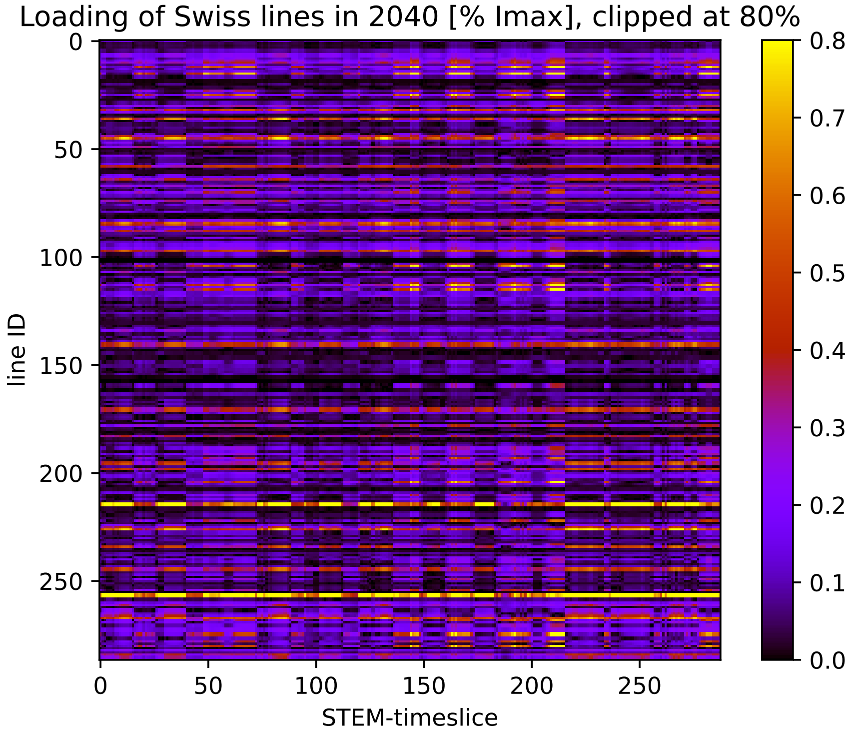


Figure 3: Electricity grid loading in the STEM scenario BAU during the year 2030. Top: The horizontal axis shows the 288 STEM timeslices, the vertical axis the 287 grid lines of the FlexECO grid model. The color denotes the line loading, yellow indicating a loading at or above the security limit of 80% of nominal line capacity. Bottom: Each bar corresponds to a line, the height indicates how often (out of 288 timesteps) it is at or above the security limit of 80% of nominal line capacity. The three colors indicate the distribution of the high line loads.



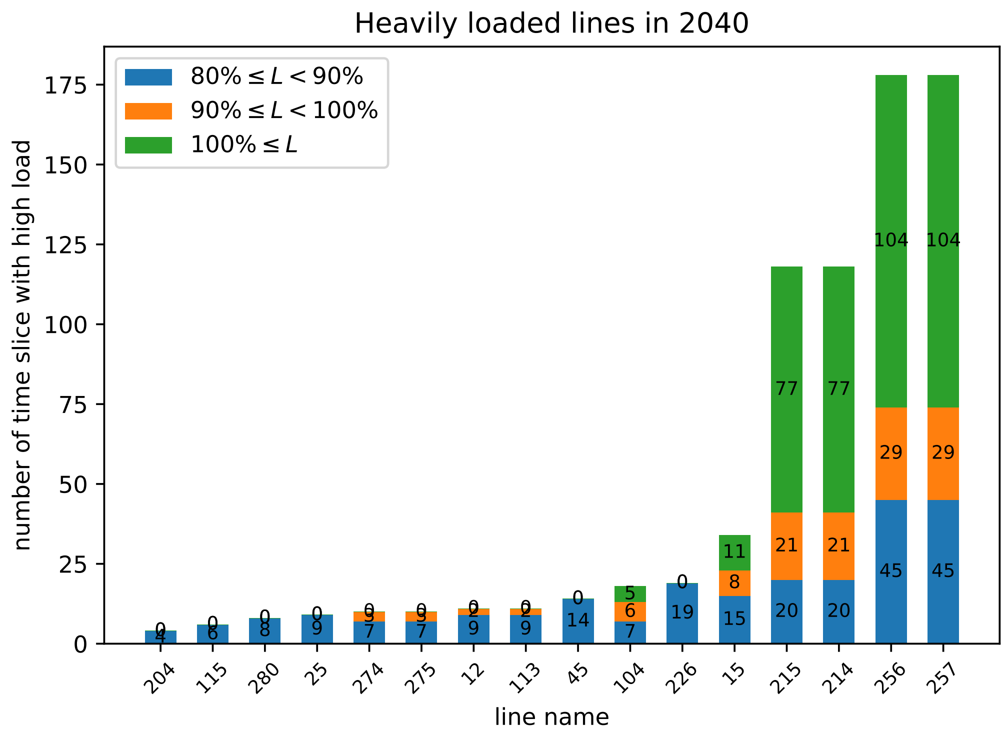


Figure 4: Electricity grid loading in the STEM scenario BAU during the year 2040. Top: The horizontal axis shows the 288 STEM timeslices, the vertical axis the 287 grid lines of the FlexECO grid model. The color denotes the line loading, yellow indicating a loading at or above the security limit of 80% of nominal line capacity. Bottom: Each bar corresponds to a line, the height indicates how often (out of 288 timesteps) it is at or above the security limit of 80% of nominal line capacity. The three colors indicate the distribution of the high line loads.

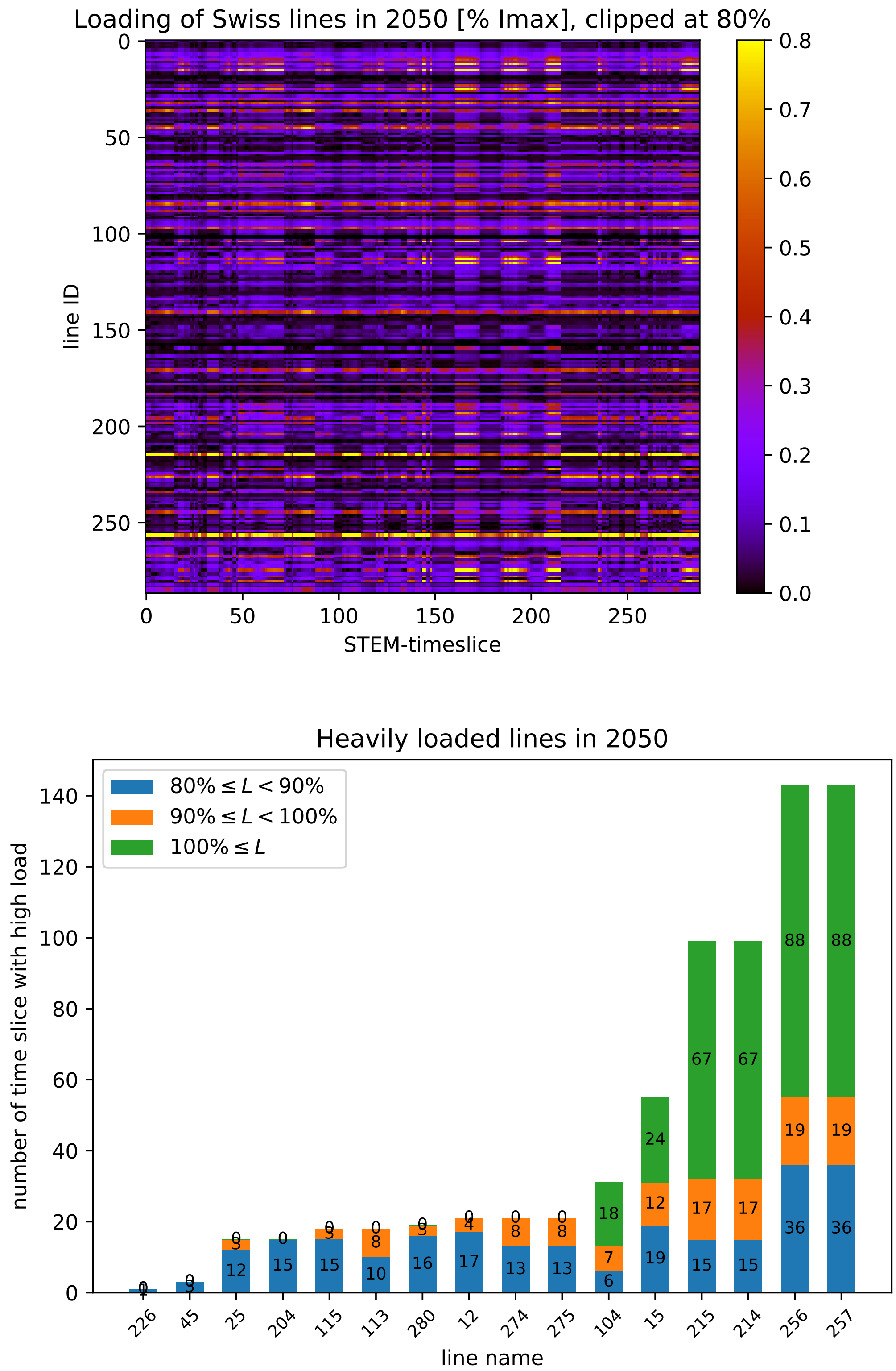


Figure 5: Electricity grid loading in the STEM scenario BAU during the year 2050. Top: The horizontal axis shows the 288 STEM timeslices, the vertical axis the 287 grid lines of the FlexECO grid model. The color denotes the line loading, yellow indicating a loading at or above the security limit of 80% of nominal line capacity. Bottom: Each bar corresponds to a line, the height indicates how often (out of 288 timesteps) it is at or above the security limit of 80% of nominal line capacity. The three colors indicate the distribution of the high line loads.

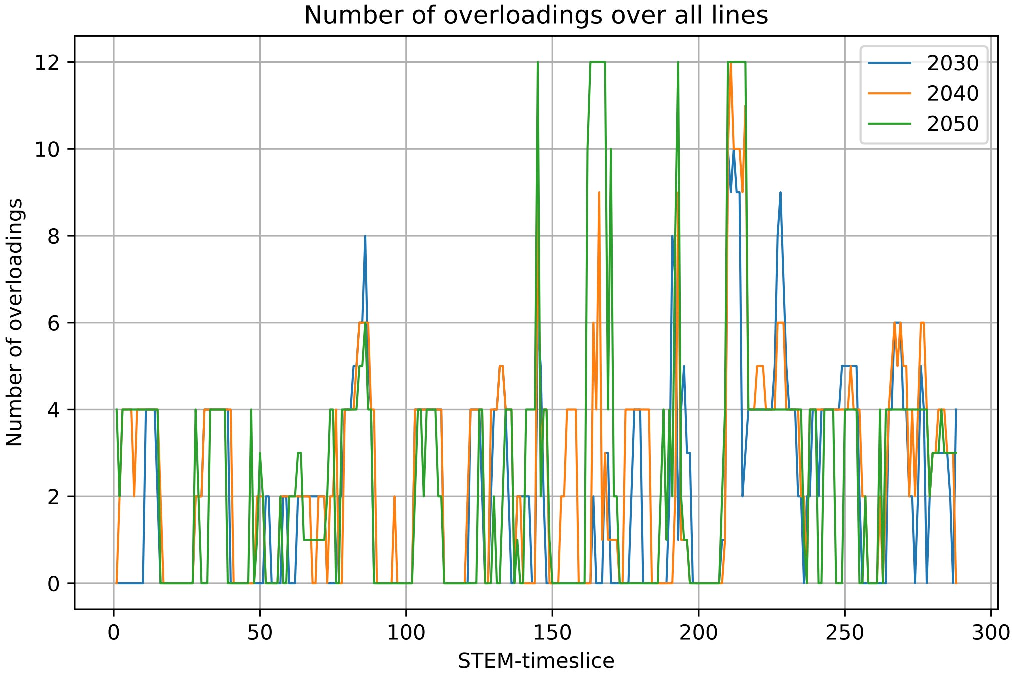


Figure 6: Aggregated illustration of the electricity grid loading in the STEM scenario BAU for the years 2030, 2040 and 2050 as a function of the STEM-timeslices.

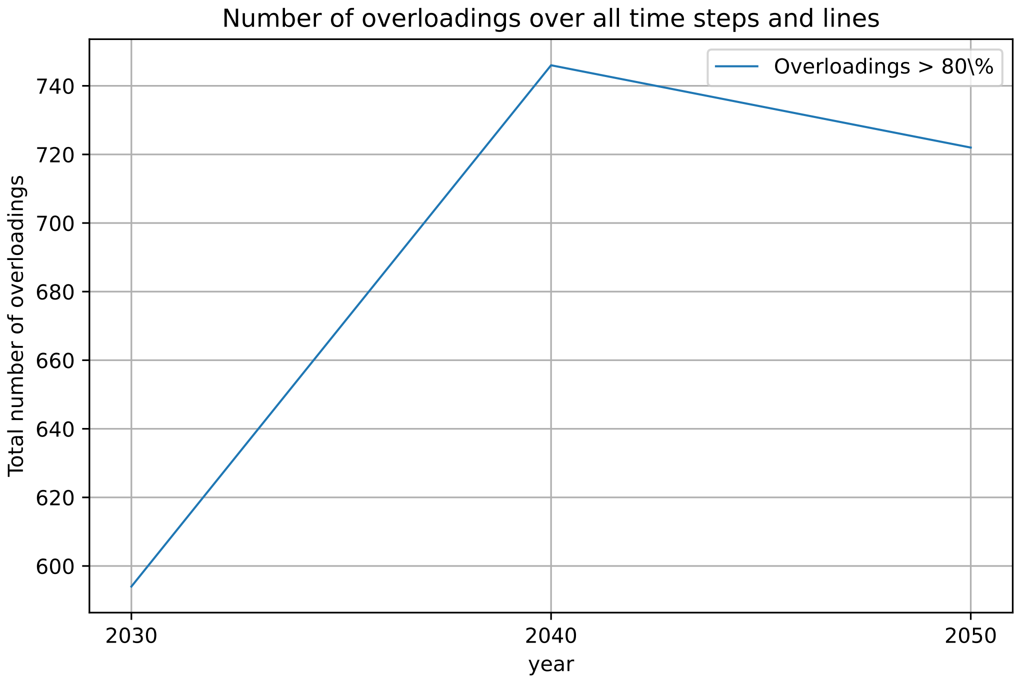


Figure 7: Candidate grid loading indicator of the STEM scenario BAU. The indicator represents the total number of overloadings above the security bound of 80% for all lines and all times steps of a give scenario year.

4.2.3 Computation of grid security indicators

The report on the computation of grid security indicators are part of the subsequent deliverable (D6.3). However, this section gives a summary of the security selected during discussion with stakeholders, SURE partners and internal reviews. Most of the indicators were motivated during the discussion of the model simplifications in the grid model computed for STEM (see Section 4.1.4). Selected indicators will be used for the SURE indicator database and the multi criteria decision analysis (MCDA).

- A base indicator is a variation of the **grid loading indicator** in Switzerland used for the grid loading indicator shown in Section 4.2.2. Instead of the 80% limit that is incorporated in the STEM model, different thresholds can be used to count lines of high loading, for instance 70%
- An **outage overloading indicator** can be computed through an actual N-1 analysis, performed for each STEM scenario and time slice. For example, the indicator can be the total number of overloadings above 100% during all possible N-1 contingencies for all Swiss lines and STEM-timeslices.
- A **robustness indicator for loop flows and transit flows** from European neighbor countries can be a copy of the nominal grid loading indicator, but for varying levels of transit flows and expected loop flows. The levels of loop and transit flows can be derived from historical data and/or analysis in the detailed European model.
- A **voltage stability indicator** can be computed using an extended FlexECO model performing AC power flow for each of the STEM scenarios. The voltage levels are compared to operational boundaries at each of the grid nodes and count the violations.
- A **robustness indicator for the spatial and temporal variation** of the load and generator distribution can be computed by randomly varying the time series of each zonal variable around the STEM average, as well as random redistributions within each STEM region. Besides randomized temporal variations, the method will also explore a pattern identification based on the Fourier transformation of historical load data [3]. The indicator itself is again a copy of the nominal grid loading indicator, but taking into account the variations.
- A **combination** of the aforementioned indicators can be performed by simultaneously performing two or more of the variations, for instance the N-1 analysis and the loop flow variation. The goal is to derive one or two combined indicators, that will be used as electricity grid security indicators in the MCDA analysis. The advantage is, that a preliminary indicator can be quickly shared with the corresponding SURE partners, to test the impact on the MCDA analysis.

5 Gas grid coupling with STEM (PSI-EEG)

This section describes, how the bidirectional coupling between the FlexECO gas grid model and the STEM energy system has been achieved.
Additionally, the section describes the improvements of the data and methods that have been achieved compared to the previous SWEET-SURE deliverable 6.1 [1].

5.1 FlexECO to STEM

The STEM energy system model captures the regional average gas demand and production. The underlying transmission grid model is dominated by the large transmission grid pipeline, connecting Germany with Italy, passing through central Switzerland, as shown by the ENTSO-G grid map [4], shown in Figure 8. The capacity of this pipeline is limited by the import and export bounds at the border points Wallbach and Oltingue in the North as well as Griespass in the South. The regional gas transmission and distribution network become only limiting during shocks and sudden demand changes. Such sudden changes are not captured by the STEM model but are analyzed in the detailed FlexECO gas grid model, as outlined in the subsequent sections.
However, to provide the STEM model with gas grid bounds for the average national imports, capacity limits and typical flow variables are extracted from the FlexECO model. They are collected from different sources and summarized in Table 1:

- The first column denotes the **border points** of Switzerland. In addition to the points from the ENTSO-G grid map [4], the last two border points are regional points from western Switzerland. The border point Thayngen-Fallentor has been omitted, since it is not in operation and has zero import bounds.

- The second column contains the **import bounds** at all border points according to the ENTSO-G capacity information 2021 [5]. It can be seen that the highest import capacity is available in Wallbach, Oltingue and Griespass.

- The third and fourth columns contain two indicators of the **actual imports** during the year 2021 based on the ENTSO-G transparency platform [6]. The year 2021 has been chosen to represent a typical year before the gas crisis of 2022.

- Columns five to seven are identical to columns two to four, only for **export flows** instead of imports. It can be seen that in 2021 exports mainly at the Griespass border point to Italy. However, recently also transit flows to the North have taken place.

To represent the **gas grid limitations within the STEM model**, the following combination of values should be considered: The nominal import and export bounds serve as base constraints, but are very high. Taken at face value, they do not impose a limitations on the gas imports for Swiss demand. However, a significant portion

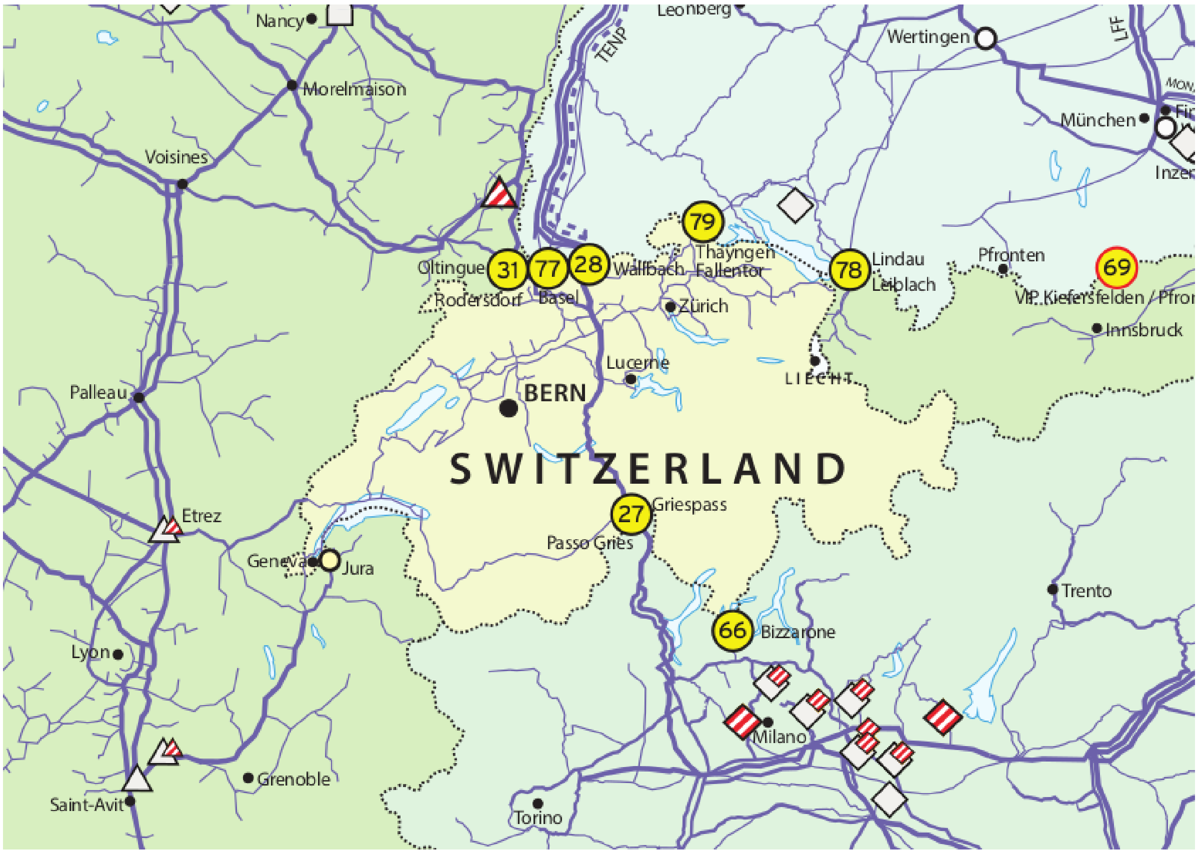


Figure 8: Section of the ENTSO-G grid map surrounding Switzerland. (Source: [4])

of the imports is typically used for transit, limiting the import capacity for Swiss consumption. This **preloading** of the transmission pipelines can be estimated by forming the difference between the total physical capacity and the corresponding transit flows.

The **physical import capacity** at the main border point used for imports is the sum of the import capacities at Wallbach and Oltingue (197.9 TWh/y). Griesspass could also be used for imports from the South (for example from LNG terminals in Italy), but will likely not be used simultaneous with the border points in the North.

To estimate the **capacity reduction due to transit flows**, the average annual values are not critical, but rather the loading during peak hours. For analysis of future scenarios it is suggested to consider one of two scenarios for import bounds.

- A **base scenario** uses the peak hourly transit flow of 2021 (158.5 TWh/y), leaving about 40 TWh/y for Swiss consumption.

- Optionally, a more **critical scenario** increases the peak transit flow by 20 TWh/y to 178.5 TWh/y, assuming for instance a higher demand in Italy. Note that this leaves only a peak hourly rate of 20 TWh/y for imports for Swiss consumption, which is less than today's annual gas consumption. However, such a low **hourly** rate is not assumed to be persistent during the whole year, but only during a shock situation like a cold spell. It would still result in a stress situation that is hard to manage due to low pressure in the regional gas transmission system.

Note that all values need to be scaled to the hourly level for application in the STEM model. The conservative bound corresponds to an hourly import limit of 2.28 GWh/h (dividing 20 TWh/y by 8760 hours).
A further refinement can be achieved by a more detailed analysis of the time series from [6] using multiple years and comparing the simultaneous imports, exports and transit flows on an hourly level. This will be part of the gas grid security indicator computation, where a temporal and spatial variation of the STEM simulation results will be performed.
Finally, external market shocks can additionally limit the availability of gas imports, regardless of the network bounds. Such restrictions, if applicable, are performed in the scenario and shock analysis of the STEM model.

Table 1: Gas grid import and export bounds and typical flows. All values in [TWh/y]. (Source: ENTSO-G [5],[6], GAZNAT)

Border point	import			export		
	physical capacity	total 2021	max daily 2021	physical capacity	total 2021	max daily 2021
Wallbach	116.5	66.4	124.2	63.1	0.6	45.2
Oltingue	81.4	15.5	94.2	36.5	0	0
Basel	3.2	0.3	3.2	0	0	0
Griespass	157.3	4.5	115.9	233.6	21.9	158.5
PIRR Jura	7.8	4.2	7.8	0	0	0
PIRR Savoie	2.0	1.1	2.0	0	0	0
Sum	368.2	92.0	347.3	333.2	22.5	203.7

5.2 STEM to FlexECO

This section presents, how the STEM simulation results are loaded and processed in the FlexECO gas grid simulator to perform the grid loading analysis and the computation of gas grid security indicators.
The initial method and data sets for steady state gas grid modeling has been outlined in the SWEET-SURE deliverable 6.1 [1]. Within the investigations of the model coupling, the indicator computation and the modeling of shocks both the dataset and modeling framework were extended and refined.

5.2.1 Import of STEM results

The STEM simulation results provide an hourly gas demand, import and domestic production, also differentiating between sectors. There is no regional granularity of the gas supply and demand within the STEM model, contrary to the electricity simulation which has seven regions.

To map the STEM **gas demand** data to the nodes of the gas grid model, the annual VSG Jahrestatistik [7] was used, which provides the annual total consumption of each canton. For cantons with multiple nodes in the gas grid model, the cantonal demand is distributed evenly between these nodes. The seasonal variation is given by the STEM timeslices. In addition, a full year distribution of the annual Swiss gas demand is created as a plausibility check, using typical seasonal distributions of European countries. Domestic **gas production** is assigned to the nodes in the same way as the demand.
Gas imports are mapped to the border points proportionally to the total import flows of 2021, as shown in Table 1. This means, that most imports occur at the border points in the North at Oltingue and Wallbach. Additional variations of the import distribution will be performed in the indicator analysis, for example modeling a novel import direction from the South to the North.

5.2.2 Grid loading analysis

Updated gas grid data The initial FlexECO gas grid model, presented in the deliverable D6.1 [1], was developed based on the SciGrid data set.
For this deliverable, an improved grid model with higher detail and accuracy of the Swiss transmission pipelines has been implemented. The structure and different operators of the Swiss transmission gas grid is illustrated in Figure 9. During implementation, a more detailed grid map was used (generated by Swissgas), that includes line diameters and the topology at connection hubs. Additional insight on the model structure has been gained through interactions during a related project with GAZNAT, the gas grid operator of western Switzerland.
Instead of capacity limits for individual pipelines, the modeling focuses on capacity limits at the border points (see Table 1) and connection hubs between the gas grid operators. Furthermore, the network is „compartmentalized“ between the connection hubs, instead of a fully open connection between all sections of the network. This way, pressure variations and operational pressure limits can be simulated in a more realistic manner.

Static grid loading analysis The gas network model for static analysis was described in the deliverable D6.1 [1]. It applies a standard model for steady state gas flows [8] and consists of two types of variables: the pressure at each node / junction and the mass flow in each pipeline. The variables are coupled by nonlinear pipeline equations, mass flow balances at each node and a pressure reference for each grid area separated by (de-)compressors.
The set of nonlinear equations is solved uses a Newton-Rhapson method, with some modifications to avoid singularities during low mass flows in certain areas of the network. The model can examine steady state flow conditions or averaged flows over a given time. In [1], the model is tested for historical time series by the International Energy Agency [9], illustrating the results with an interactive web browser

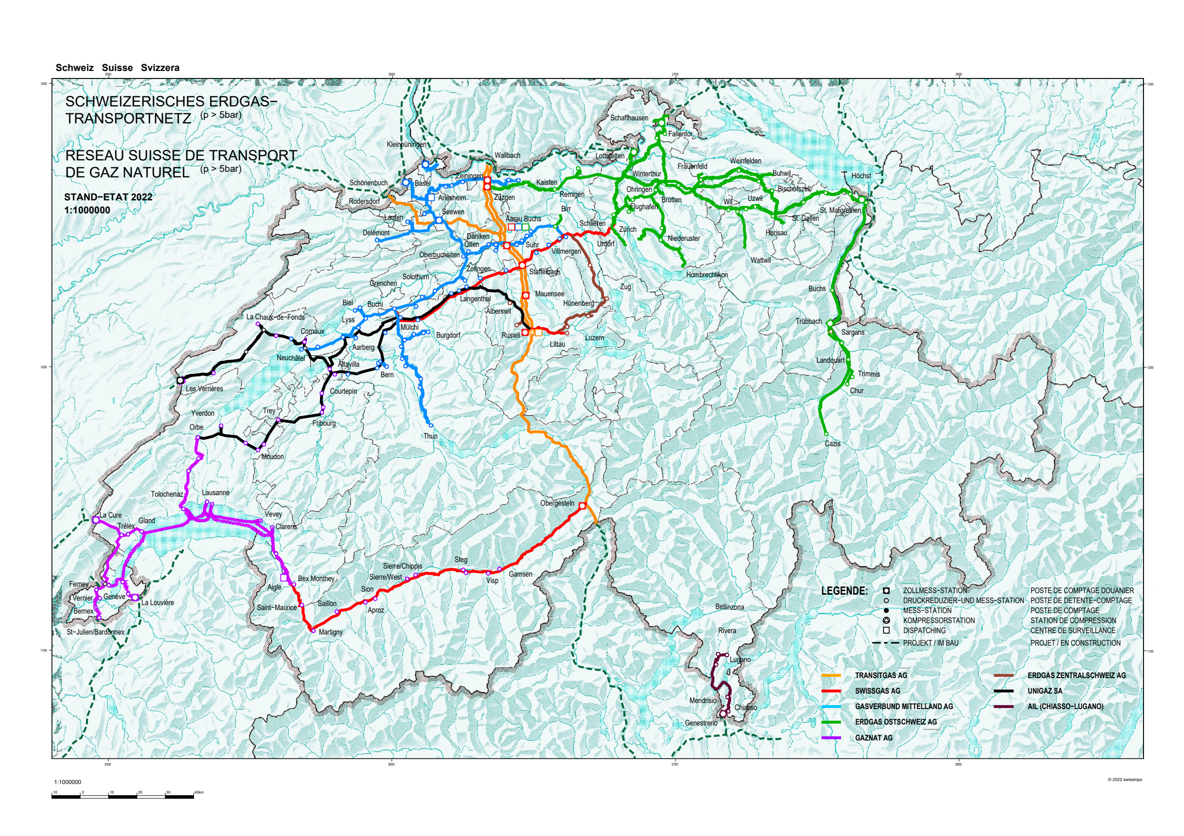


Figure 9: Overview of the Swiss gas transmission network (Source: Swissgas).

visualization.

Dynamic grid loading analysis A review of operational challenges from literature and discussion with Swiss gas grid operators has identified the need for a higher spatial and temporal granularity of the gas grid simulator than the simple static modeling approach. Critical situations can occur during the short-term operation, involving transients and temporary imbalances arising from sudden changes in demand and supply, such as through gas power plants or large power-to-gas units. Such transients can take hours to settle, depending on parameters such as gas pipe diameters, nominal gas flow and the size of the network. Gas power plants are also part of the Swiss concept for electricity grid security in exceptional emergency situations, developed by ElCom [10].

Therefore, the static gas grid model has been extended to a dynamic model to simulate changes in the "Linepack" (the amount of gas stored within the gas network), as well as local and global pressure pressure transients. After initial attempts to extend the static model with an isolated simulation of the Linepack-effect, it was found, that an adequate modelling requires a full dynamic gas pipeline model. In this approach, the static Weymouth equation for each pipeline is replaced by a one-dimensional partial differential equation (PDE) model, where each variable has a temporal and a spatial dimension [11]. For the implementation, the two PDEs coupling the pressure and the mass flow of each pipeline are discretized using the **finite difference method**:

- Each pipeline is **discretized** into 10 segments. The time resolution depends on the network complexity and is typically chosen to be 10 seconds. For a 6-hour simulation (=2160 time steps) of a network with 25 pipelines, this corresponds to 25*10*2160*2 = 1'080'000 variables (pressures and mass flows at each node of the discretized system).

- As **initial condition**, the pressure distribution along the pipeline is chosen as linear interpolation between the pressure of the two nodes. Similarly, the initial mass flow is set to be constant along the pipeline.

- As **boundary condition**, the positive or negative injections at each import or demand junction is imposed as constraint along the simulation horizon. This includes dynamic demand changes, such as activated gas power plants, power-to-gas units or adjustments of the import flows.

- **Additional conditions** include the pressure reduction ratios, the nodal mass flow balance and the nodal pressure equalities at the junctions. In total, the numbers of equations equal the number of variables (1'080'000 in the above example).

As for the static model, the nonlinear system of equations is solved using a Newton-Rhapson method. The implementation is performed in Python, using the sparse matrix library and the linear algebra package of SciPy. Gas storages are modelled as positive/negative injections into the network that may vary over time, with the same considerations regarding the location close to the Transitgas pipeline. The dynamic PDE model can be simplified to the static model when taking the steady state limit. This equivalence has been validated in the simulation of simple example systems and a full Swiss gas transmission grid model. Therefore, both the static and the dynamic model can be used to investigate the impact of varying planned demand, gas power plants, storages, and varying import flows on the operational network security.

Figure 10 shows an illustrative example simulation result of the Swiss gas transmission. The picture shows the pipeline starting at Obergesteln (next to the transit gas pipeline close to Italy), crossing Valais and continuing west to La Cure (at the French border). The node with the lowest pressure is in the center at around 170 km. After the initial activation of a 300 MW gas power plant in the northern part of the network, the pressure is continuously dropping due to the reduction of the Linepack in the pipeline. The pressure distribution and its evolution depends on the initial gas flows, the size and location of the gas power plant, and how the additional gas demand is compensated, for example using additional imports.

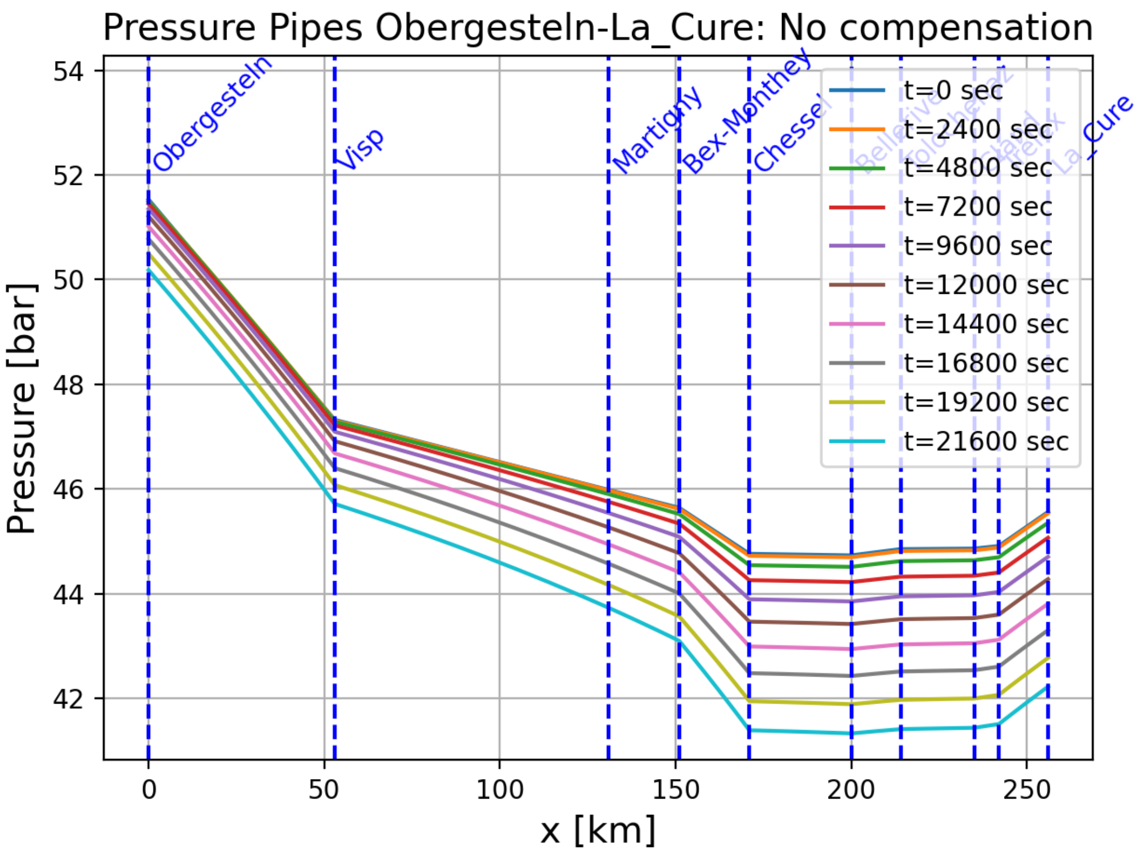


Figure 10: Simulated pressure distribution along the southern pipeline (from Obergesteln in the east to La Cure in West) after activation of a gas power plant.

5.2.3 Computation of grid security indicators

The computation of grid security indicators will be performed in the subsequent deliverable D6.3. However, a preliminary presentation of the parameters and variables involved is presented in this section.
In general, a grid security indicator should quantify how robust the gas flow scenarios of the STEM simulation is to local changes in demand and supply balance. If the pressure at any node in the network gets too low, the full supply of households and other demand will no longer be possible.
Therefore, the nominal flow scenarios computed by the STEM model will be disturbed with different variations of the gas balance to create transients such as the example depicted in Figure 10. The **variations of the gas balance** will include the following:

- Unscheduled changes in demand through gas power plants.
- Unscheduled changes in local supply through power-to-gas units.
- Sudden loss of imports, local supply or demand through problems in the gas network.

If no compensation occurs, the overall pressure in the network would continue to increase or decrease, as in the example in Figure 10. The **compensation** can come from additional imports, the activation of a gas storage or a temporary reduction/increase of flexible demand. Each compensation changes the injections at different locations in the network and can only be activated with a certain delay.
To illustrate this concept, Figure 11 shows the pressure evolution at two nodes of the network (Altavilla and Tolochenaz) during a high-demand scenario and after the unscheduled activation of a 300 MW gas power plant, for different compensation scenarios:

- After the start of the 300 MW power plant, the pressure decreases in Altavilla at a rate of about 1.3 bar per hour. At Tolochenaz, the rate is about 0.75 bar per hour, but keeps accelerating, as the pressure transient propagates through the system. In the scenario without compensation (yellow line), the pressure drop continues until critical levels are reached.
- In the second scenario (green line) with a fast compensation from the transit pipeline (after 15 minutes, for instance using a local storage), the pressure in Altavilla stabilises at 49 bar. In Tolochenaz, the stabilisation takes place at a slower rate and requires more than 5 hours. The further the node is from the compensation point Ruswil, the more pronounced the pressure drop becomes.
- The third scenario (red line) shows the compensation with a delay of three hours, which is a typical time to purchase gas on the market. The pressure takes much longer to settle, reaching lower values in the process.

A **potential gas grid security indicator** could be computed from the example in Figure 10 as the distance between the lowest pressure reached by the red line (slow compensation) and minimal pressure value (say, 40 bar). The following parameters need to be selected to compute the indicator:

- **Initial gas flows in the network**. The higher the flows, the larger the initial pressure drops. The indicator will be computed for selected timeslices of the STEM simulation results, typically those with the average and the maximum gas demand. An additional increase of the gas demand will be considered, since the STEM timeslices are an average value over multiple hours.

- **Type, size and location of the imbalance**: gas power plant, power-to-gas unit, temporary pipeline loss.

- **Type, delay and location of the compensation**: Imports, storages, adjustment of demand/production.

In total, this allows to compute a family of security indicators. It is intended to discuss these indicators with gas industry experts to select one or two indicators for the subsequent SURE multi criteria decision analysis.

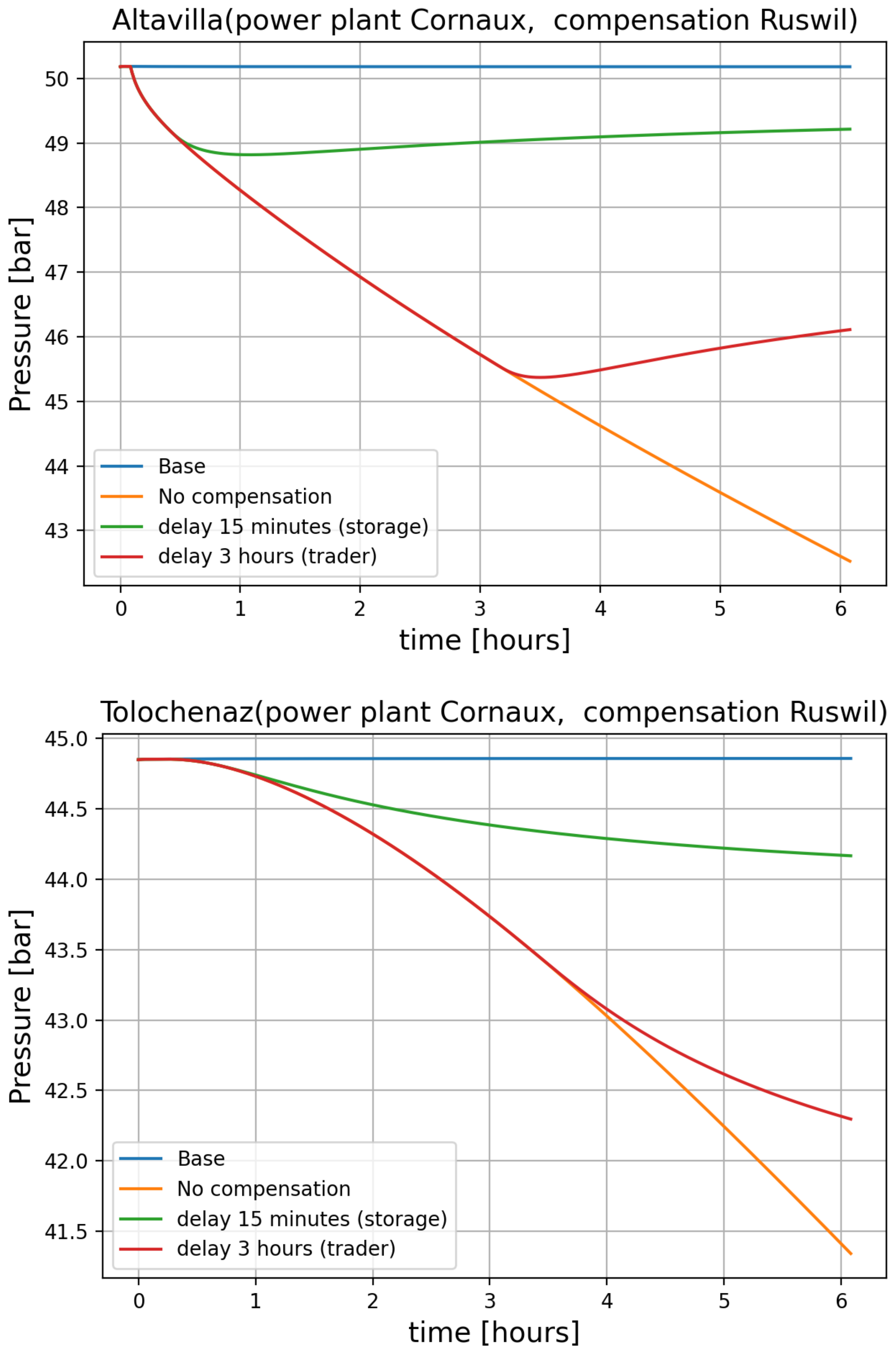


Figure 11: Pressure at the node Altavilla (near the power plant) and Tolochenaz (junction of three main gas pipelines): comparison of three compensation scenarios after the activation of a 300 MW gas power plant.

6 Coupling with other models

6.1 Coupling with EXPANSE (Uni Geneva)

The coupling of the FlexECO electricity grid model with EXPANSE of Uni Geneva is similar to the electricity grid coupling with STEM. EXPANSE performs a full energy system simulation with varying weather and demand scenarios in order to determine the optimal PV distribution within Switzerland. The model performs a time series simulation of a full year (8760 time steps). It has a fine spatial resolution for PV, but only a simplified representation of the grid on a zonal level, that should be complemented with the FlexECO grid model.
To align the coupling procedure with the STEM-coupling (see Section 4), EXPANSE assigns the time series to NUTS2 regions, using the same 25 injection variables as for the STEM model (imports/exports, loads, flexible and fixed generation). This way, the whole simulation tool and indicator computation developed for the STEM-coupling is immediately applicable to the EXPANSE simulations to provide grid security insights. A particular expected benefit will be, how the variable PV distribution developed with EXPANSE differs from the default distribution of STEM, when seen from a grid security perspective. A first exchange of time series has been established and full results will be presented in the subsequent deliverable on indicators, D6.3. Future potential refinements include an improved nodal assignment of PV, Wind, Biomass and BESS (available on the level of municipalities in EXPANSE), and the computation of network capacities between the regions represented in EXPANSE.

6.2 Coupling with the Building Stock model (TEP Energy)

The coupling of the FlexECO electricity grid model with the Building Stock Model of TEP Energy is a case study specific coupling of WP14. Using a district of the city of Zurich, the case study develops a cost efficient heat grid planning tool, given a future heat demand. To this end, the electricity grid planning algorithms of FlexECO will be adopted to be used for heat grid planning. The method is combined with an existing planning tool at TEP Energy and will be presented in subsequent deliverables of WP14.

6.3 Coupling with the MCDA (PSI-TAG)

The coupling of the FlexECO Grid models with the SURE-MCDA (multi criteria decision analysis, performed by PSI-TAG) is a formal coupling. Essentially, it is a forwarding of the FlexECO simulation results to the SURE database in the appropriate format for further processing. However, the process also includes feedback on the quality of the indicators, comparison with other indicators and robustness assessments. Overall, the indicator selection in SURE is a highly interdisciplinary process, that was accompanied by multiple workshops of WP1 with internal SURE partners and external stakeholdes.

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