A REGULATOR'S GUIDE TO THE USE OF LOAD FLOW STUDY TOOLS FOR TRANSMISSION PLANNING

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1 Introduction

The National Regulatory Authorities (NRAs) from the regions of Europe and Eurasia (E&E)[1] are actively working to improve the performance of electricity markets. As most of these countries are contracting parties to the Energy Community, their transmission system operators (TSOs) are obliged to regularly assess long-term generation adequacy and prepare long-term network development plans in each individual country in line with the applicable rules set out by the European Union. The NRAs have the responsibility to monitor this process, and, in most cases, review and approve the final development plans. In line with the EU's objectives, most of the NRAs are also directly involved in promoting the development of functioning electricity markets and the regional integration of national markets.

Through its cooperative agreement with the United States Agency for International Development (USAID) Bureau for Europe and Eurasia, the National Association of Regulatory Utility Commissioners (NARUC) implements the Enhancing Stability and Technical Expertise in European and Eurasia Energy Markets (ESTEEM) for USAID-assisted countries and USAID Missions. With funding support from USAID, NARUC seeks to provide technical advisory support to the NRAs in the E&E region to extend their knowledge and improve their capabilities in these fields.

While the benefits of market coupling are clear, the decisions to move forward can be challenging in a technical and political regard. It is, therefore, paramount that regulators, TSOs, and other industry stakeholders have an open dialogue, and that NRAs have a robust understanding of the benefits and challenges that market coupling can bring in order to prepare for the impact of such scenarios. Similarly, E&E regulators must be able to critically review and assess the long-term development plans put forward by the TSOs and other network operators.

Against this background, NARUC has commissioned the authors to prepare primers that address the principles, use, and understanding of two important types of analytical tools commonly used by TSOs and/or other relevant stakeholders in this context. This document (Primer I) focuses on the use of load flow studies for transmission planning, on the one hand, and the evaluation of changes to market design, including in particular market coupling or other means of regional integration, on the other. In parallel, another primer (Primer II – A Regulator's Guide to the Use of Production Simulation Tools for Market Analysis) has been prepared to discuss the use of market simulation tools for generation expansion planning and market simulations as shown in Figure 1.

[1] For the purposes of this project, this includes the National Regulatory Authorities (NRAs) from Albania, Armenia, Bosnia & Herzegovina, Georgia, Kosovo, Moldova, Montenegro, North Macedonia, and Ukraine.

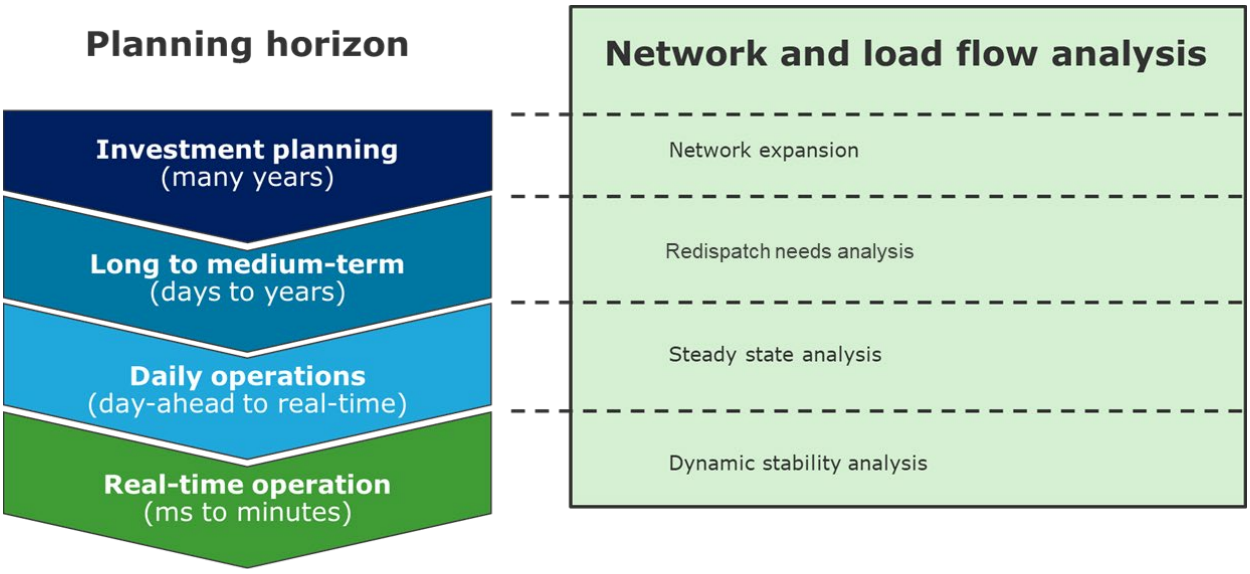

Figure 1: Modeling categories of energy system and how they can interact

The remainder of this primer is structured as follows:

- *Chapter 2* contains the necessary background to understand the basic principles, rationale, benefits, and types of modelling tools for load flow studies that are commonly used in the electric power industry.
- *Chapter 3* presents the key inputs and parameters that are required for using power system simulation software.
- *Chapter 4* comments on the use of tools for load flow studies when applied for the specific purposes of transmission planning and the assessment of market reforms.
- *Chapter 5* provides an overview of the typical outputs of load flow studies tools and their relevance for the tasks of the regulators.
- *Chapter 6* discusses the role of the regulator for accompanying, monitoring and approving the use of load flow studies within the context of their corresponding tasks in the electricity market.
- *Chapter 7* presents some concluding remarks.

Finally, it should be noted that the term 'load flow studies' principally designates a specific type of power system studies, i.e., related to the determination and analysis of power flows and voltage levels of a transmission (or distribution) grid. Within this document, however, this term is also used to refer to other types of analysis that are relevant for long-term transmission planning and market reform studies, such as contingency analysis and dynamic studies.

2 Fundamentals and Available Tools

2.1 Basic rationale, structure, and features

Transmission planners use load flow or power system studies for a wide range of analyses; see Table 1. As indicated, one traditionally differentiates between static and dynamic analysis as follows:

- steady state analysis is used to assess power flows at a single moment in time, whereas
- dynamic analysis assesses the transient behavior of the power system after an event

Table 1: Typical features of network analysis for transmission planning studies

Steady State Analysis	Dynamic Analysis
Load flow analysis	Voltage stability
Contingency analysis	Frequency stability
Short circuit analysis (steady state)	Rotor angle stability
NTC calculation	Short circuit power (transient)
Re-dispatch	

Note: Red rectangle indicates traditional core functionalities for transmission planning
Source: DNV GL

Traditional planning studies used to focus on the three aspects highlighted by the red rectangle at the top left of Table 1, i.e., load flow, contingency and (steady state) short circuit analysis. Implicitly, these different applications are related to the following terms and definitions by CIGRÉ-IEEE task force on stability:[2]

*"**Reliability** of a power system refers to the probability of its satisfactory operation over the long run. It denotes the ability to supply adequate electric service on a nearly continuous basis, with few interruptions over an extended time period."*

*"**Security** of a power system refers to the degree of risk in its ability to survive imminent disturbances (contingencies) without interruption of customer service. It relates to robustness of the system to imminent disturbances and, hence, depends on the system operating condition as well as the contingent probability of disturbances."*

*"**Stability** of a power system refers to the continuance of intact operation following a disturbance. It depends on the operating condition and the nature of the physical disturbance."*

More detailed market and/or market-oriented studies may, however, also require other types of simulations, like NTC calculations and re-dispatch needs. In the following subsection, we briefly comment on each of the items listed in Table 1.

[2] P. Kundur et al., "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," *IEEE Transactions on Power Systems* 19, no. 3 (August 2004): 1387–1401, https://doi.org/10.1109/TPWRS.2004.825981.

2.1.1 Steady state analysis

In general terms, steady state refers to a state which remains unchanged in the future. In power systems, it refers to a state when load and generation are in balance and the power system is relatively stable.

Load flow analysis

Load flow calculations are the most commonly used calculation method in power system simulation software. AC load flow studies are used to determine all power flows, voltage levels, and voltage angles of lines and nodes in a power system. Due to the non-linear relation between active power, reactive power, voltage magnitude, and angle,[3] an iterative solving process is applied, which is commonly based on the Newton-Raphson method. The solution time generally varies depending on the size and complexity of the power system being analyzed. A major disadvantage of AC load flows is the risk of non-convergence, i.e., that the AC load flow may not find a solution.

As an alternative, DC load flow may be used. As DC load flow studies are always convergent and do not require any iterations, they are often used wherever repetitive and fast load flow estimations are required. This is, for example, the case when a longer time span e.g., a complete year and/or multiple scenarios are evaluated. DC load flow studies provide an estimation of real power flows as they only consider active power flows and neglect reactive power flows. Consequently, this method is less accurate than AC load flow studies.[4] Nevertheless, the accuracy of DC load flows usually is sufficient for transmission networks, while this is not usually the case at the distribution level.

Contingency analysis

A common steady state analysis is the contingency analysis, which is used to verify if the power system is secure after the occurrence of a contingency, such as the failure of a line, transformer, generator, or facility for reactive compensation. Besides a single failure, commonly referred to as an 'N-1 contingency,' contingency analysis may also extend to an N-2 contingency, i.e., the simultaneous loss of two generators or transmission lines. Similarly, it may also cover so-called "common mode" failures, such as the breakdown of a tower carrying multiple circuits or a busbar failure in a substation.

Short circuit analysis

Short circuit analysis serves to investigate the impact of different types of short circuits on the power systems, including minimum and maximum single-phase or symmetric (three-phase) short circuits or multi-pole short circuits with/without earth contact. For steady state analysis, this type of analysis is normally used to assess the rating of individual assets (e.g., lines, circuit breakers, switches etc.), setting of protection schemes, or grounding conditions. In addition, it may also be required for voltage quality and overall stability assessment.

NTC calculation

While load flow studies are principally used to investigate real physical flows on the transmission grid, cross-border trading in the wholesale electricity market is often based on the notion of so-called net transfer capacities, or NTCs. The corresponding NTC values are determined by means of load flow studies where the exchange between two different areas is gradually increased until it becomes limited

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[3] Hossein Seifi and Mohammad Sadegh Sepasian, *Electric Power System Planning: Issues, Algorithms and Solutions - Appendix*, Power Systems (Berlin Heidelberg: Springer-Verlag, 2011), https://doi.org/10.1007/978-3-642-17989-1.
[4] Seifi and Sepasian.

(i.e., N-1 violation) by one or more network constraint. Many tools for load flow studies therefore include specific functionalities for an automated determination of NTC values across defined borders, or interfaces. While the determination of NTC is part of operational planning, it is also relevant for transmission planning and market studies, i.e., as an input in market simulations.

Re-dispatch

Similarly, zonal electricity markets may lead to internal congestion within a given market area or bidding zone which cannot be resolved through the wholesale market. In these cases, it then becomes necessary to resolve such issues by means of re-dispatch, i.e., by adjusting generation (or load) at one or more specific locations in the network. Although re-dispatching is principally a feature of daily operations, it should also be considered for planning studies, irrespective of whether these are carried out for transmission planning and/or for assessing the impact of market design or regional integration.

2.1.2 Dynamic analysis

Stability refers to the ability of a system to return to a steady state following a disturbance. According to the CIGRÉ-IEEE task force on stability terms and definitions[5], the following stability phenomena can be identified and defined as follows:

- Frequency Stability
- Voltage Stability
- Rotor Angle Stability

In addition, dynamic stability analysis may also be applied for short circuit analysis as discussed in the previous section.

Frequency stability

Frequency is a global system parameter, which is the same in the whole power system at every voltage level. Frequency stability refers to the ability of a power system to balance load and demand. Frequency stability issues may occur in different timescales from seconds to hours and are caused for example by:

- loss of generation (under-frequency);
- loss/disconnection of a large load (over-frequency);
- deviations between forecast (under/over-frequency); and
- loss of interconnection (under/over-frequency).

Most frequency deviations can be restored by an operating reserve to nominal frequency. More severe frequency deviations may need addition reserve products (e.g., emergency reserve) or adjustments to the generator dispatch, or load shedding to restore the operating reserve and/or nominal frequency.

[5] Kundur et al., "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions."

Voltage stability

Voltage is a local system parameter, which is influenced by the flow of reactive power across the network. Reactive power imbalances may lead to voltage excursion in a given area of a power system. For example, major power flows may lead to decreasing voltages in networks dominated by overhead lines.

Voltage stability issues can be categorized[6] as follows:

- long-term voltage stability issues:
    - "chain reaction" resulting from overloaded branches, tap actions of transformers etc. ("cascading faults")
    - develops in either several minutes or up to several hours and is usually of a global nature ("voltage collapse")
- short-term voltage stability issues:
    - loss of voltage stability in the short-term, e.g., subsequent to a line trip or generator outage.
    - Short-term voltage instability develops in either hundreds of milliseconds or up to a few seconds.
- dynamic voltage stability issues ("induction machine instability"):
    - During voltage sags, induction generators accelerate, and induction motors decelerate, both approaching their stalling point. When operating close to the stalling point, induction machines absorb a much higher amount of reactive power than prior to the disturbance. Consequently, induction machines can have a negative impact on voltage recovery in a system or even initiate local voltage instability.
    - Dynamic voltage instability develops in a matter of seconds. Therefore, it represents a special type of short-term voltage instability.

Rotor angle stability

Synchronous machines tend to swing against each other in the case of even small disturbances. In order to mitigate this phenomenon, directly coupled synchronous generators are equipped with damping windings and in many cases with additional Power System Stabilizers (PSS). These are control devices that modulate the excitation voltage to improve system damping.

Rotor angle stability describes the ability of a power system to maintain synchronism following large disturbances, such as grid faults. Due to the nonlinear nature of power systems, rotor angle stability depends not only on system properties but also on the type of disturbance. On account of the complexity of the problem, rotor angle stability can only be analyzed by a series of time domain simulations using dynamic models of generators, governors, and controllers.

[6] Moeller & Poeller Engineering GmbH, "Power System Security in Developing and Emerging Countries," vRE Discussion Series, VRE Discussion Series (Bonn / Germany: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH), accessed May 14, 2020, https://energypedia.info/images/1/15/Discussion_Series_05_Technology_web.pdf.

2.2 Common Tools and Approaches

Transmission planners may choose from a wide range of modeling tools, including PSS®E, PowerFactory, NEPLAN, Powerworld, and many others. PSS®E and PowerFactory are amongst the most commonly used power systems simulation tools found around the world and are also widely used in the region relevant to this primer. Both tools provide similar functionalities and provide both the basic functions described in the previous section, such as load flow or contingency analysis, as well as a range of additional functionalities.

According to one study,[7] both tools provide similar results for steady state and dynamic analyses, despite applying varying underling calculation methods. In addition, both tools support advanced visualization and various functionalities for the import and export of data and simulation results.

[7] Björn Karlsson, "Comparison of PSSE & PowerFactory," 2013, http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-209640.

3 Input Data Requirements

3.1 Key input data

Depending on the scope and focus of the analysis, the configuration of load flow models may require different types of input data; see Table 2. The following information is necessary for load flow and security analysis:

- grid data, including the overall network topology and technical parameters of grid assets, such as the impedance, rating and regulating capabilities of lines, transformers, HVDC installations and facilities for reactive power compensation
- information on nodal injection (generation) or offtake (load) of active and reactive power at all relevant nodes of the network

More detailed analysis, like short-circuit analysis or dynamic simulations, require additional information on generators, loads, control mechanisms and algorithms, etc. Finally, transmission planners also have to define relevant contingencies and the technical limits that need to be enforced.

Table 2: Core input data for configuration of load flow and power system models

Category	Parameter needs for network planning related load flow simulations
Energy market related time series (MW time series, hourly values)	• Dispatch for each directly connected plant unit incl. industry plants, large storages etc. • For each grid node, aggregated dispatch time series per RES category for plants connected to underlaying network • In-feed for each directly connected RES farm; for not directly connected RES power (smaller RES farms, roof top PV panels, etc.) aggregated in-feed values for each grid node and per RES category • Load for each directly connected C&I; for not directly connected consumers aggregated load values for each grid node • Dispatch of infeed/load equivalents connected to underlaying and surrounding grids • Import/export schedule per control area, HVDC schedules, NTC related phase-shifting transformer taps
Grid data	• Grid topology incl. lines, substation nodes, busbars, busbar couplers, connected power plants, RES farms, C&I • Steady-state parameters of all primary grid assets (HVAC lines, HVDC systems, transformers incl. phase-shifting ones, compensation assets like reactance coils, MSCDN, SVC, STATCOM etc.): Esp. nominal and rated voltages, thermal rating for continuous and short time operation, any tapping schemes, R_1, X_1, C_1 as absolute values or specific values + lengths [km] • Electrical parameters of grid equivalents for connected underlaying and surrounding grids • For short circuit simulations: S_r, U_r, u_k, copper losses, R_0, x_d'' or S_k'' (max/min/current value), X_1/R_1, X_0/R_0, R_0, X_0, C_0
Generation data (for each directly connected generator or RES farm)	• Power capability curve (P_{min}, P_{max}, Q_{min}, Q_{max}) • FCR and FRR share of each generation unit • Voltage control mode (PQ, PV, cosPhi) • Unit transformer data (nominal voltages, S in MVA, tap numbers, voltage per tap position, copper losses, u_k) • For short circuit simulations: S_{rated}, U_{rated}, u_k, P_k, R_0, x_d'' or S_k'' (max/min/current value), X_1/R_1, X_0/R_0
Operational aspects	• Normal switching state and relevant special topological measures • NTC values for control area profiles and any temperature depending power flow limit on interconnections • Implemented or planned dynamic line monitoring • Special protection schemes (esp. over-current, under-voltage)

Source: DNV GL

Transmission network topology and data

As stated above, the configuration of a power system model starts with the underlying network structure, i.e., the topology of all lines, substations, transformers, switchgear etc. In principle, the corresponding data represents the design and structure of the real grid, as indicated by the simplified grid map for the transmission grids in South-Eastern Europe, as shown in Figure 2.

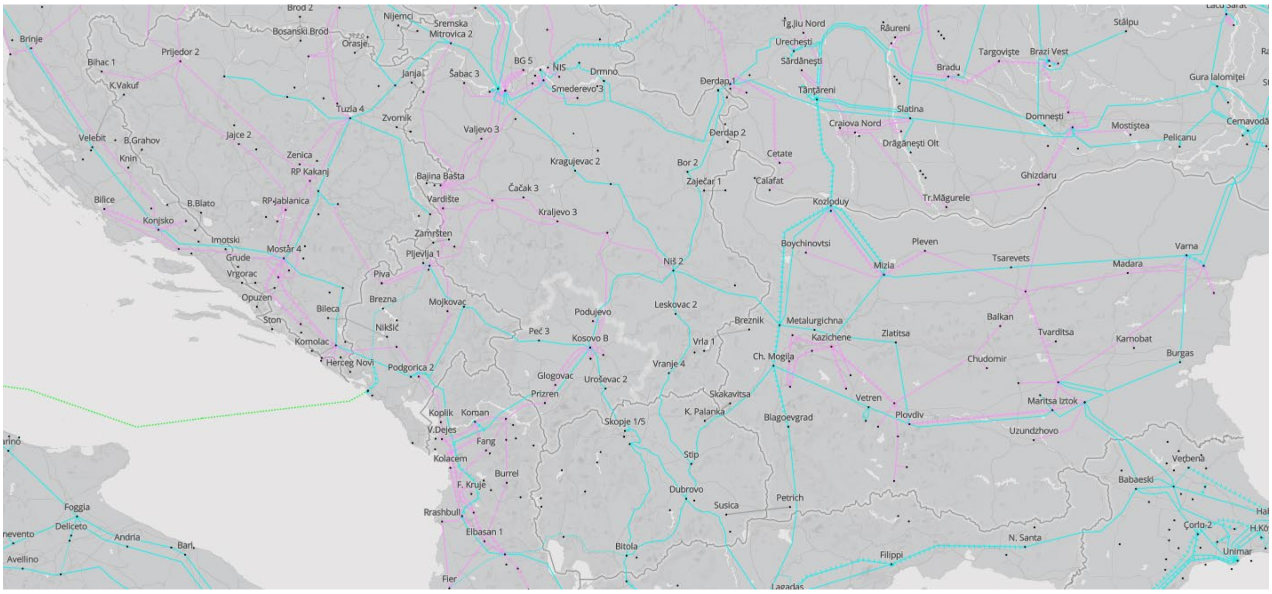


Figure 2: Simplified grid map of South-Eastern Europe

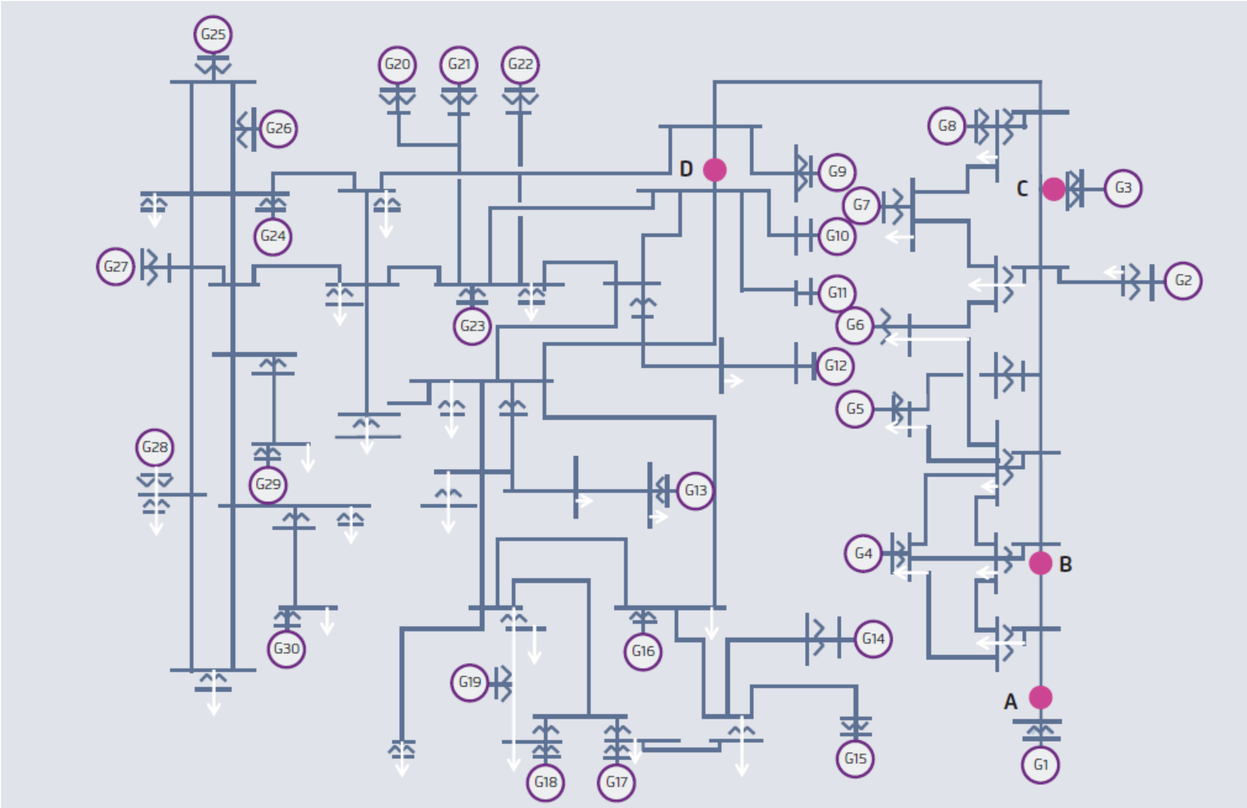
Source: ENTSO-E[8]

For network simulations, however, the geographical structure of the transmission grid and the location of its individual assets are of limited relevance. Instead, a robust analysis requires careful consideration of the electrical parameters of all relevant assets and precise representation of the principal network topology. In practice, the latter is usually visualized by means of so-called single line diagrams, as the example in Figure 3 demonstrates.

In contrast to a geographical map, which attempts to mirror the exact geographical location and/or route of all relevant elements, a single line diagram consists of a simplified graph reflecting the grid topology, i.e., consisting of all grid nodes and the connections (e.g., lines or transformers) between different nodes. As such, the visual layout of a single line diagram may thus be substantially different from the network's geographical structure, and the distances between different nodes may not be at all representative of the physical length of the underlying assets.

In order to reduce the complexity of the underlying calculations, information on transmission and distribution networks is often aggregated or reduced. For example, load flow studies for transmission purposes often ignores all elements at sub-transmission and distribution level. Likewise, neighboring grids may be represented by so-called 'reduced networks' or equivalent systems which represent the basic characteristics of the corresponding networks, but in a much simpler form.[9]

[8] ENTSO-E, *Interconnected Network of Continental Europe*, December 31, 2018, December 31, 2018.
[9] The so-called network reduction is another typical feature of most tools for load flow studies.



<u>Figure 3: Single line diagram for the Eastern Synchronous Area of Japan</u>

Source: Renewable Energy Institute[10]

Apart from grid topology, the distribution of load flows and/or the transfer capability of individual transmission assets or interfaces depends on the electrical parameters of the corresponding elements. Similar to grid topology, these properties obviously depend on the design and construction of the corresponding assets, such as the physical design, diameter, conductor material etc. of lines, the type of transformers, environmental conditions (e.g., temperature, wind speed), etc. as well as the voltage at which they are operated. For the purpose of load flow studies, however, it is necessary to define a limited number of electrical parameters, including most importantly impedance (resistance and reactance), the permitted rating or maximum capacity, tap settings of transformer, etc. For dynamic studies, additional models of transmission lines might be required, including for instance information on the actual arrangement of conductors or phases.

Technical limits, critical branches, and contingencies

The ultimate objective of all types of network analysis is to identify any possible violations of defined boundary conditions and technical limits which may endanger the secure and reliable operation of the power system. It is thus necessary to clearly define the permissible limits, for instance with regard to the thermal loading of lines and transformers, voltage and frequency, rotor angle, etc.

Furthermore, these limits may vary over time or for different types of analysis. For example, the maximum allowed loading (or rating) of lines and transformers may depend on external conditions,

[10] Agora Energiewende, "Integrating Renewables into the Japanese Power Grid by 2030" (Renewable Energy Institute, April 2019).

such as temperature or wind speed. Similarly, different limits are often applied for load flow and security analysis, i.e., for N-0, N-1, or N-2 conditions. For example, it is common practice to allow for temporary overload under N-1 conditions, and permitted voltage ranges may be greater as in the example from Germany in Figure 4.

Fore base case (n-0):	U_{min} = 390 kV … U_{max} = 420 kV U_{min} = 220 kV … U_{max} = 245 kV
For (n-1) case:	U_{min} = 380 kV … U_{max} = 420 kV U_{min} = 210 kV … U_{max} = 245 kV

Figure 4: Example of voltage limits for load flow and security analysis in Germany

Source: DNV GL

Similarly, the transmission planner has to decide for which 'critical branches' such technical limits shall be enforced and, for security analysis, which contingencies to consider. For instance, in transmission planning, thermal limits are often enforced for transmission lines only, but often neglected for transformers, network elements at sub-transmission, and even at the distribution levels.

Similar considerations apply to the selection of 'critical contingencies.' While it may appear desirable to consider all possible contingencies, this is often neither possible nor useful in practice. Firstly, a large number of contingencies will have a direct impact on the number of combinations to be considered and hence on computation times. Moreover, while being mathematically possible, many combinations are not relevant in practice. This is simply because the resulting impact on the 'critical branch' will be minimal, while others may be impossible to resolve, for instance in the case of radial lines. In practice, contingency analysis is therefore usually limited to credible contingencies,[11] i.e., events that are likely to occur and cause a significant impact on the power system.

[11] AEMC, "Security," AEMC, accessed May 26, 2020, https://www.aemc.gov.au/energy-system/electricity/electricity-system/security.

Generation and load

Even for the simplest type of analysis, load flow studies require information on the amount of generation and load at every grid node. In the case of generation, these parameters mainly include the maximum available capacity and the scheduled and/or expected output of each generating unit. For loads, the expected demand of a single consumer or the aggregated consumption connected at a concrete grid node needs to be modeled. While the corresponding information is often well known for generating units and loads that are directly connected to the transmission grid, the situation is quite different for distributed resources that are connected to sub-transmission and/or distribution networks. In the latter case, the capability and impact of such resources must be estimated, including the distribution to one or more transmission nodes.

Similarly, many types of analyses require further information, for instance on the type of technology of generation (e.g., conventional generation such as coal fired power plants or non-conventional generation like solar PV). For some types of studies, it is also important to differentiate between synchronous or non-synchronous generators. Synchronous generators have capabilities which are relevant for power system stability (e.g., synchronizing torque or inertia). Similarly, different generators may have different capabilities to provide reserves and/or reactive power.

Dynamic models

Dynamic models are required for stability analyses, e.g., to assure that short circuits close to generation units will not lead to instability of connected generators or that switching operations will not lead to pole wheel oscillations in the transmission system which might trigger the protection of a generating unit ("off signal"). There are simplified methods that can be applied in order to assess such aspects based on short-circuit calculations.

However, if the simplified methods show critical results, detailed dynamic simulations need to be carried out, commonly referred to as so-called stability analyses. For stability studies, dynamic models of power system components are required with parameter sets which go beyond the parameter needs for conducting steady-state or short-circuit analyses, including in particular:

- dynamic model of synchronous machines including mechanical and controller related parameters (turbine control);
- models of excitations systems, AVR (automatic voltage regulators) and PSS (power system stabilizers;
- models of wind turbine generators and their controls including inverter parameters;
- models of PV inverters; and
- other

3.2 Collection and estimation of input data

Table 3 provides an overview of typical sources for the different types of input data discussed above. It seems reasonable to assume that all necessary information on the grids is either available to the TSO itself or must be collected from other network companies, including from neighboring countries where applicable (e.g., in case of interconnectors and/or neighboring grids). Similarly, the selection of critical branches and contingencies is typically subject to the discretion of the transmission planner, potentially based on its own operating practices or agreements with other relevant stakeholders, such as other network operators.

Table 3: Typical sources for selected types of input data

Type of data	Key sources
Transmission network topology and data	TSO, other network operators
Technical limits	Technical rules, planning and operational & standards
Critical branches and contingencies	Selection by TSO (in agreement with other relevant stakeholders) Operating practices
Generation and load	Provided by generators and consumers (transmission-connected) Aggregate information by DSOs / TSO estimate
Dynamic models	Provided by generators and consumers (transmission-connected) Technical rules & standards Standard libraries for common tools (manufacturers)

Source: DNV GL

Conversely, most of the applicable technical limits are usually based on well-defined external sources. Indeed, for most types of power system studies, applicable standards, grid code requirements, standard literature, internal planning requirements, or procedures exist. These documents usually define boundary conditions or requirements for all types of studies.

As indicated in Table 3, technical information on transmission-connected generation and load is usually provided by the operators of corresponding facilities (i.e., power plants, industrial loads, distribution network operators) to the TSO, at least for existing units or for facilities under construction or at an advanced stage of planning. Indeed, in most cases, this information is already available to the TSO, or the corresponding network operator, for operational purposes. In contrast, for future projects which have not yet applied for grid connection, this information is usually based on the TSO's own estimates or assumptions.

However, the situation for distributed resources is clearly different, i.e., decentralized generation and distribution-connected consumers. In this case, the necessary information typically has to be provided to the TSO by the underlying DSOs. Consequently, close coordination and cooperation between all network operators concerned is required. Alternatively, for instance, the German TSOs may decide to spend major resources on either developing or purchasing its own bottom-up estimates for the future development of distributed wind and solar resources; see Figure 5.

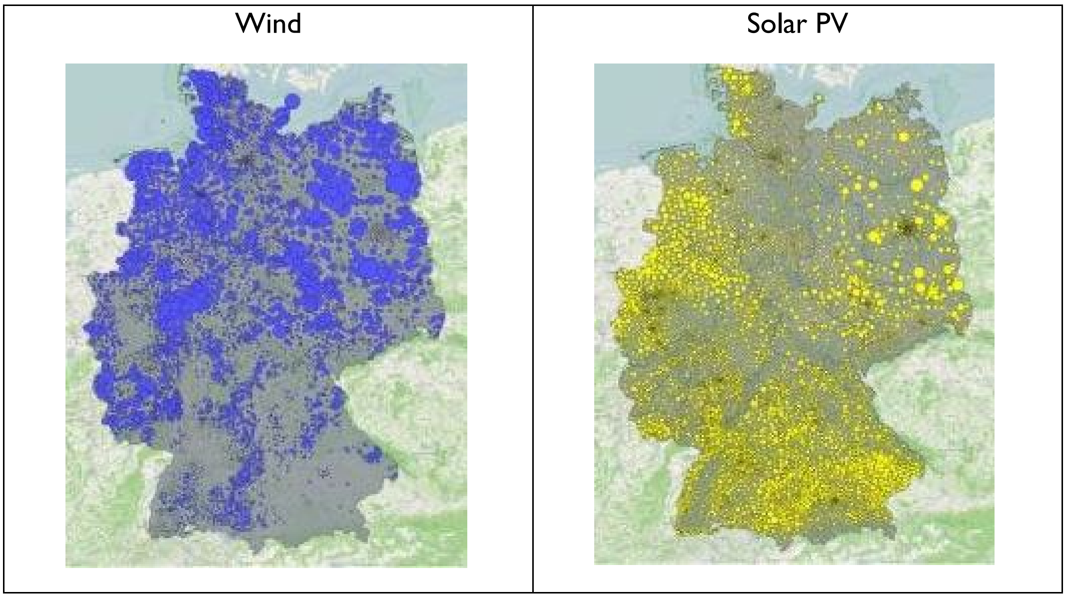


Figure 5: Regionalization of wind and solar power for German grid development plan

Source: German Network Development Plan 2015 for 2025[12]

Transmission planners also need to have access to the necessary inputs for dynamic analysis. For existing assets, such information may again be available from the data exchanged for operational planning and real-time operations. Nevertheless, such information is not generally available for future plants and distributed resources. Moreover, the effort required for the development and maintenance of dynamic models is relatively high.

For this reason, IEEE or IEC have prepared detailed standard models, which are included in the libraries of common power system tools, including a description on how to use such models in stability studies e.g., IEEE 421.5–2016;[13] see the example in Figure 6. For some types of studies, (e.g., grid connection studies) the project developer must provide either the certified parameters for the standardized models or provide the certified manufacturer model itself. As not all dynamic models can be mapped onto standardized models, many TSOs also maintain their own library with user-defined models.

[12] Four German TSOs, "Grid Development Plans 2025 | Grid Development Plan," accessed June 16, 2020, https://www.netzentwicklungsplan.de/en/grid-development-plans/grid-development-plans-2025.

[13] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," *IEEE Std 421.5-2016 (Revision of IEEE Std 421.5-2005)*, August 2016, 1–207, https://doi.org/10.1109/IEEESTD.2016.7553421.

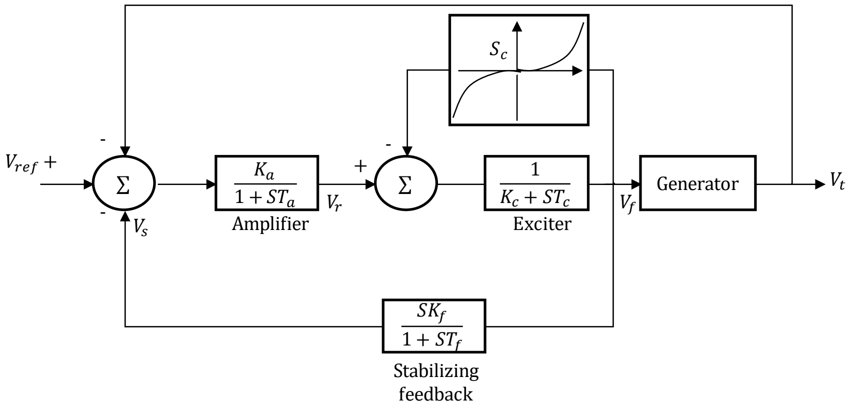
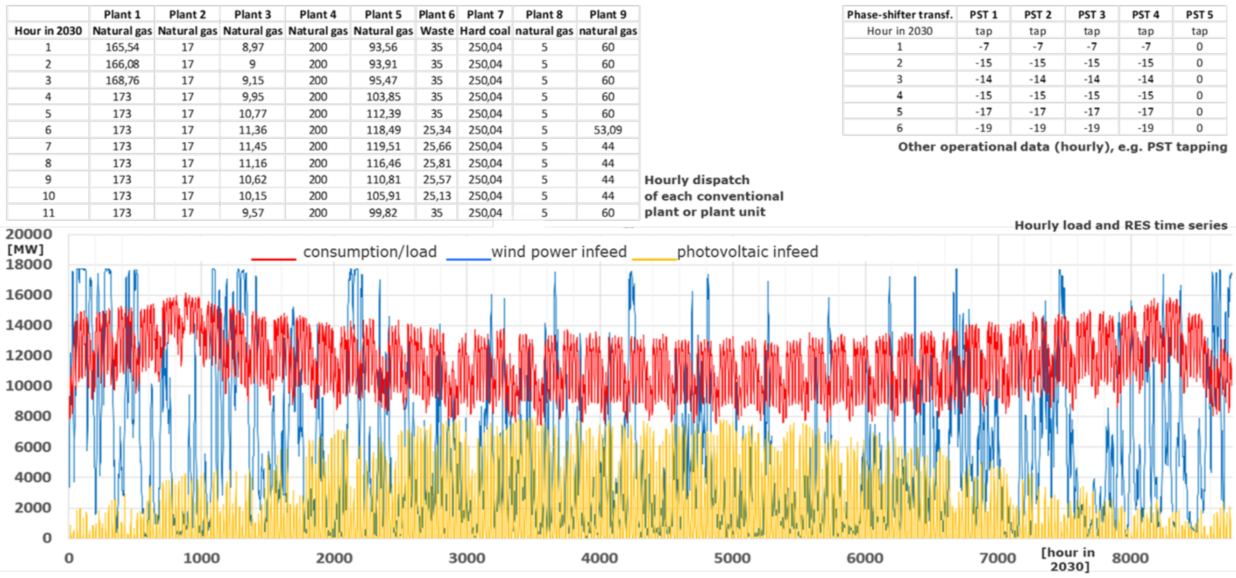


Figure 6: Automatic voltage regulator IEEE type 1

Source: DNV GL

Finally, Figure 7 shows an illustrative overview of key inputs from market, which is used by the German TSOs for their network development plan. The German power system is one of the largest in Europe, with more than 2,000 generating units or injections and the separate treatment of 124 load regions, all of which are considered for 8,760 hours. This clearly illustrates the massive scope of the analysis undertaken by the German TSOs.



	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8	Plant 9
Hour in 2030	Natural gas	Natural gas	Natural gas	Natural gas	Natural gas	Waste	Hard coal	natural gas	natural gas
1	165,54	17	8,97	200	93,56	35	250,04	5	60
2	166,08	17	9	200	93,91	35	250,04	5	60
3	168,76	17	9,15	200	95,47	35	250,04	5	60
4	173	17	9,95	200	103,85	35	250,04	5	60
5	173	17	10,77	200	112,39	35	250,04	5	60
6	173	17	11,36	200	118,49	25,34	250,04	5	53,09
7	173	17	11,45	200	119,51	25,66	250,04	5	44
8	173	17	11,16	200	116,46	25,81	250,04	5	44
9	173	17	10,62	200	110,81	25,57	250,04	5	44
10	173	17	10,15	200	105,91	25,13	250,04	5	44
11	173	17	9,57	200	99,82	35	250,04	5	60

Phase-shifter transf.	PST 1	PST 2	PST 3	PST 4	PST 5
Hour in 2030	tap	tap	tap	tap	tap
1	-7	-7	-7	-7	0
2	-15	-15	-15	-15	0
3	-14	-14	-14	-14	0
4	-15	-15	-15	-15	0
5	-17	-17	-17	-17	0
6	-19	-19	-19	-19	0

Figure 7: Overview of market-related input data for transmission planning in Germany

Source: German Network Development Plan 2017 for 2030 (diagram reflects 50Hertz control area)

4 Load Flow Simulations for Transmission Planning and Market Analysis

4.1 Embedding load flow studies into overall scenario analysis

Planning and market design studies often rely on scenario analysis. In this context, it is important to consider that, for the purpose of this document, load flow studies cannot be carried out in isolation but are always embedded into a wider process, which, directly or indirectly, involves market simulations as well. This can be explained by the fact that, as explained in the previous chapter, load flow studies are based on one or more given dispatch situations. These dispatch situations are essential input for the analysis and must hence be derived in advance, i.e., either by means of expert assumptions or some form of market modeling.

To illustrate this, please see the example provided in Figure 8. This chart shows how power system modeling is integrated into the overall modeling approach for transmission planning. Namely, starting with the initial scenario building and the definition of all relevant input assumptions, the first step of the quantitative analysis consists of market simulations, i.e., in order to derive a series of dispatch situations. In the third step, this information is then used for detailed power system modeling as discussed in this document, before being used for subsequent cost benefit analysis or other assessments in the final stage.

Similarly, the same principal approach is often used for investigating the impact of market design changes, such as regional integration or market coupling. In the latter case, the 'scenarios' developed in the first stage primarily aim at reflecting different choices with regard to market design, while the remaining part of the analysis would broadly remain the same.

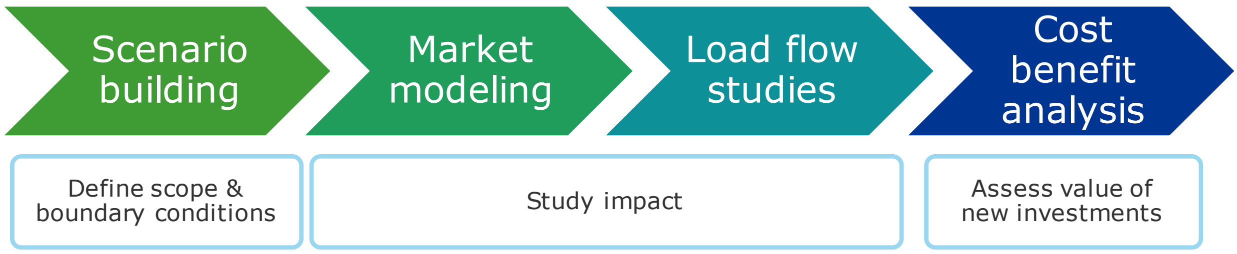


Figure 8: Load flow studies as a part of the overall process for transmission planning

Source: DNV GL

In line with these considerations, we simply refer to chapter four of the Primer on Market Simulations for a more comprehensive discussion of the overall scope for the use of scenario and sensitivity analysis for transmission planning and market design analysis. Similar to market simulations, scenario analysis is a key tool in this context for dealing with future uncertainties. For illustration, Figure 9 shows how the East German TSO 50Hertz uses scenario analysis to cover an increasing number and impact of uncertain developments as the planning horizon extends into the future.

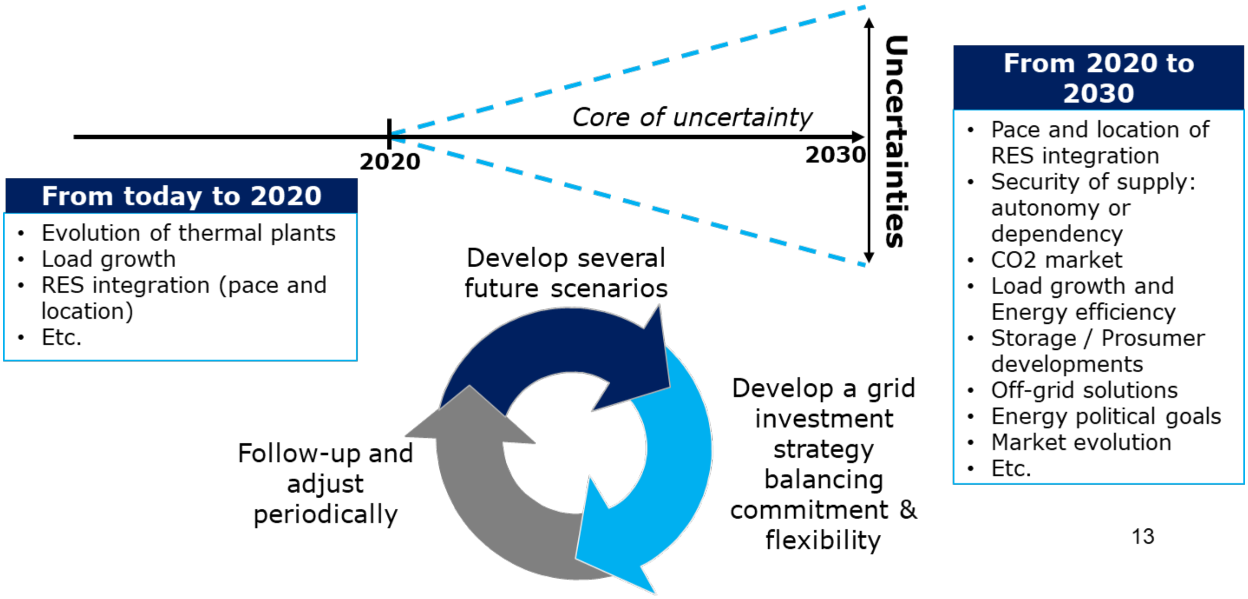


Figure 9: Example of considerations for scenario analysis by German TSO

Source: DNV GL

4.2 Scope of load flow studies

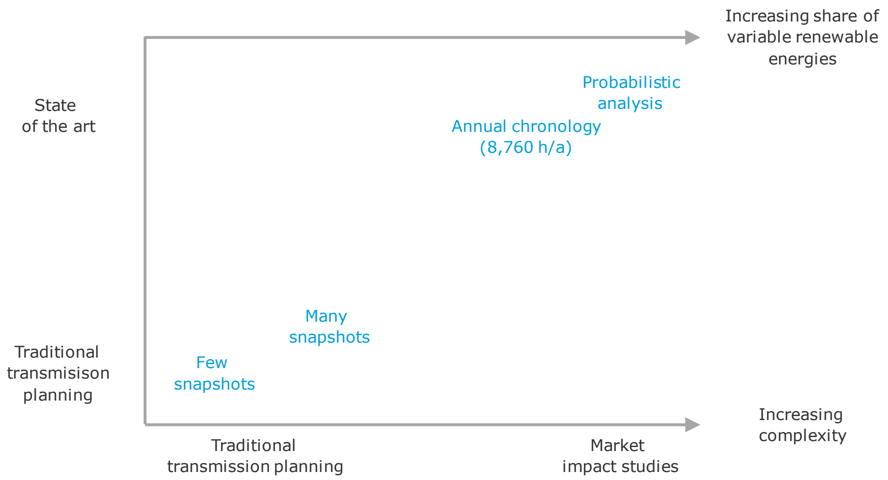
Traditionally, load flow studies and other types of power system studies focus on a few extreme scenarios, such as maximum and minimum load conditions during winter and summer, or other relevant seasons or periods. This choice was traditionally driven by limited computational resources and major efforts for conducting detailed AC load flow studies. At the same time, this choice appeared to be justified because the primary objective of such studies was to check for the ability of the system to ensure a degree of reliability even under extreme conditions.

In parallel with the regional integration of national electricity markets and an increasing share of generation from variable renewables, however, this approach has increasingly become obsolete. Regional integration facilitates exchanges between power systems. These may be influenced by very different circumstances, such that critical situations may occur at different points in time. Similarly, wind and solar power cause much more volatile system conditions, and periods of minimum or maximum residual load and/or times with a maximum need for load following can no longer be tied to pre-determined times. As a consequence, network operators have been increasingly forced to expand the number of snapshots considered, i.e., from just a few to 'many' (see bottom left of Figure 10).

As a result of continued regional integration of local electricity markets and a growing impact of different types of variable Renewable Energy (RE) sources at different locations, system operators in continental Europe and parts of the U.S. have also become aware that it is becoming increasingly difficult to identify a range of 'critical situations.' Furthermore, market impact studies or comprehensive cost benefit studies of major network investments require a broader perspective. Namely, while the consideration of critical situations may be sufficient for assessing the security and reliability of a power system, the economic impact of investments or market reforms primarily depend on the 'average' effect of the corresponding changes.

Facilitated by the continued improvement of the underlying analytical tools, system operators are thus increasingly using complete chronological studies for entire years, i.e., in a similar way as was traditionally used for market simulation studies. To also cater for longer-term variations, such as the influence of different weather years, probabilistic approaches are sometimes also used. Probabilistic approaches help to identify worst-case conditions with a reasonably high likelihood to occur and/or to determine a distribution of possible operating conditions.

The combinatorial or randomly (e.g., Monte-Carlo-Simulation) generated conditions might be analyzed automatically or manually by a power system simulation software to determine its impact on power system reliability, security, or stability. As also illustrated by Figure 10, these developments have resulted in a greatly increased degree of complexity of the time dimension for transmission planning.



<u>Figure 10: From traditional to state-of-the-art approaches for transmission planning</u>

Source: DNV GL

Besides the temporal scope, it is furthermore important to consider another dimension which is of key importance for transmission planning studies. Namely, while market impact studies usually only look at one or several changes, transmission planners may have to assess and model a potentially large number of changes in order to address any issues identified. The scope of such grid adaptations may cover a larger number of individual projects, ranging from simple grid optimization via selected grid reinforcements to large-scale grid extensions.

5 Interpretation and Assessment of Results

As explained in section 3.1, load flow studies are primarily used to evaluate, whether line loadings or voltage levels remain within the statutory, regulatory, or technical limits. Most of the common software tools, including PSS/E and PowerFactory, support corresponding functionalities for presenting, visualizing and/or assessing important results.

In the following section, we briefly present some typical examples which may be useful for different types of analysis, including:

- the use of so-called 'heat maps;'
- visualization of line loadings;
- lists of critical elements and contingencies;
- visualization of curtailment and re-dispatch needs; and
- charts showing the dynamic system response.

Heat maps for voltage and/or line loadings

Figure 11 shows a single line diagram and the voltage profile as a heat map in PSS/E. The colors of the heat map indicate if the calculated voltage is above or below nominal voltage. The calculated voltages shown in this figure are expressed in p.u., which is equal to the ratio between the calculated voltage and nominal voltage of a given node or element.[14] In many countries, voltages up to 10% above nominal voltage are allowed during normal operation, which is equivalent to 1.10 p.u.

The heat map's colors in Figure 11 how critical areas may be easily identified. The areas in dark red, for example, indicate where busbar voltages are at 1.05 p.u. and are hence approaching the allowed voltage operating limits of the corresponding system. Similarly, dark cases of blue are used to identify areas of undervoltage. The heat map therefore also makes it possible to put these observations into context with the overall situation in the wider grid.

As another option of voltage report, Figure 12 shows an example of ranked N-1 voltage results in PowerFactory.

[14] A value of 1 p.u. means that the calculated voltage is equal to the nominal voltage, while values greater (less) than 1 indicate that the calculated voltage is above (below) the nominal value.

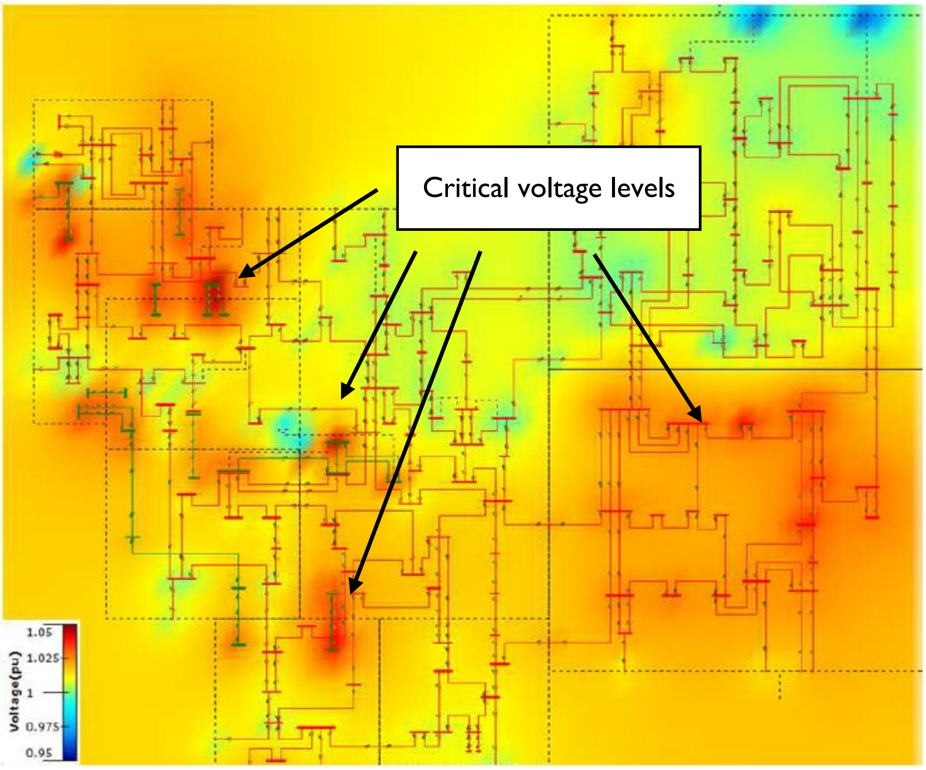


Figure 11: Example of voltage profile diagram in PSS/E

Source: SEE Electricity Market Perspectives until 2030, p. 147; additional highlight by DNV GL[15]

	Component	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Name	Base Case and Post Voltage [0,969 p.u. - 1,211 p.u.]
1	Component 154	1,211	0,169	1,043	157	Element 1622	
2	Component 287	1,211	0,169	1,043	157	Element 983	
3	Component 334	1,163	0,159	1,004	902	Element 764	
4	Component 544	1,163	0,159	1,004	902	Element 712	
5	Component 125	1,157	0,158	0,998	902	Element 648	
6	Component 766	1,144	0,118	1,026	902	Element 735	
7	Component 127	1,138	0,156	0,982	902	Element 723	
8	Component 458	1,132	0,058	1,074	1116	Element 927	
9	Component 1469	1,128	0,154	0,974	902	Element 892	
10	Component 145	1,127	0,043	1,084	902	Element 93	
11	Component 151	1,125	0,119	1,006	902	Element 783	
12	Component 142	1,124	0,119	1,006	902	Element 142	
13	Component 113	1,123	0,154	0,969	902	Element 24	
14	Component 714	1,122	0,088	1,034	902	Element 257	
15	Component 215	1,119	0,043	1,076	902	Element 634	
16	Component 166	1,117	0,056	1,061	1089	Element 1616	
17	Component 817	1,116	0,056	1,060	1089	Element 781	
18	Component 818	1,111	0,070	1,041	1116	Element 954	
19	Component 519	1,111	0,070	1,041	1116	Element 565	
20	Component 20	1,110	0,049	1,061	1042	Element 812	
21	Component 28	1,110	0,049	1,061	1042	Element 634	
22	Component 220	1,110	0,049	1,061	1042	Element 665	

Figure 12: Example of ranked N-1 voltage results in PowerFactory

Source: DNV GL

Visualization of line loadings

Figure 13 shows a similar form of visualization. This case, a simplified geographical grid map, is used to show lines which would be overloaded in the case of N-1 contingencies, again using different shades

[15] Djordje Dobrijevic, Hrvoje Keko, and Martina Mikulić, "SEE Electricity Market Perspectives until 2030," n.d., 163.

of yellow and red to highlight critical elements. In this particular example, the results on the left-hand side of Figure 13 show that many transmission lines could be overloaded during critical hours of the year. To reduce the impact of the contingencies, the right chart shows the same results taking various network reinforcements and extension proposed by the TSOs into consideration. A comparison between the two charts clearly demonstrates that the proposed grid upgrades/expansions are able to considerably resolve the situation.

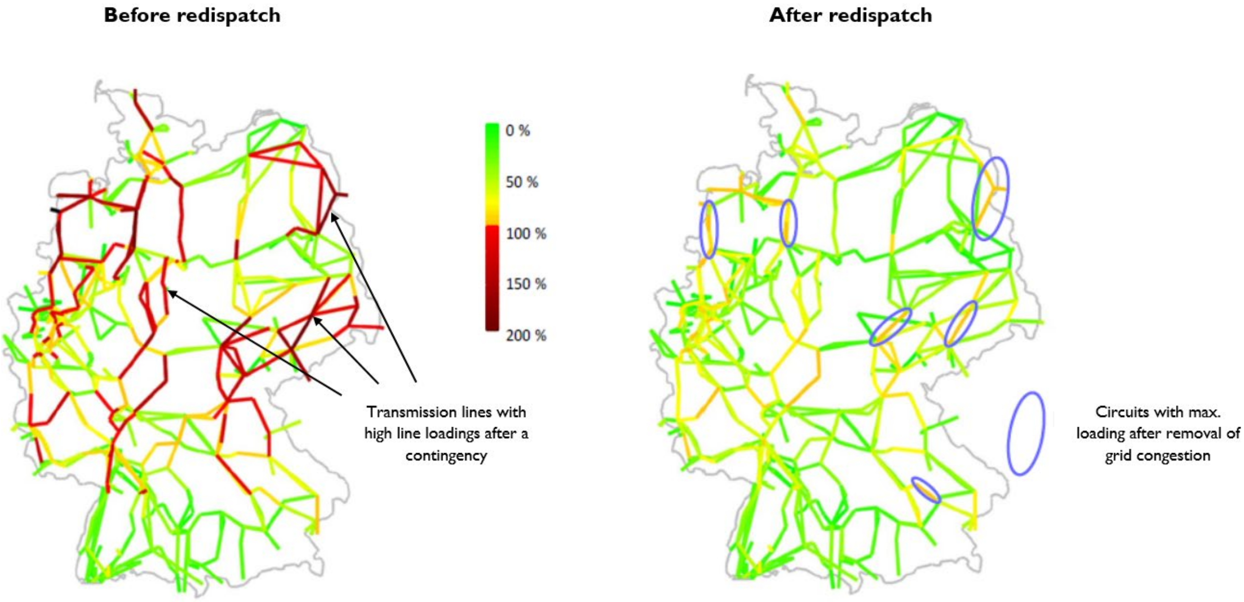


Figure 13: Illustration of line loadings before and after grid optimization

Source: Based on report by the Four German TSOs[16]; additional explanations by DNV GL

Besides any graphical representations, common load flow tools also support the presentation and exportation of structured lists, showing selected outputs for all or only critical network elements. To illustrate this, Table 4 shows a list of critical contingencies. Amongst others, the entries in the table indicate the "contingency element" itself, the monitored element (on which the overload is registered), and the calculated flow and loading on the latter. In addition, the table also specifies the nominal voltage and type of different elements (e.g., lines vs. transformers) as different thresholds may apply.

[16] 50Hertz Transmission GmbH et al., "Abschlussbericht - Systemanalysen 2018," 2018, 55.

Table 4: Sample result of contingency analysis

Monitored element Type: 1 - Transformer 2 - Overhead line							Rating A	FLOW	Loading	Contingency element
Start node		kV	End node		kV	Type	MVA	MVA	%	
26059	SK 1-A	110	3WNDTR	SKOPJE 5	WND 2	1	300	300.7	100.2	Overhead line 26003-26065
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	308.8	102.9	Overhead line 26003-26065
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	303.2	101.1	Overhead line 26013-26115
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	305.1	101.7	Overhead line 26017-26066
26059	SK 1-A	110	3WNDTR	SKOPJE 5	WND 2	1	300	300.1	100	Overhead line 26032-26065
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	308.2	102.7	Overhead line 26032-26065
26059	SK 1-A	110	3WNDTR	SKOPJE 5	WND 2	1	300	301.1	100.4	Overhead line 26059-26063
26111	SK 1	400	3WNDTR	SKOP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	verhead line 26059-26063
26059	SK 1-A	110	3WNDTR	SKOP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	verhead line 26062-26063
26111	SK 1	400	3WNDTR	SKOP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	verhead line 26062-26063
26059	SK 1-A	110	3WNDTR	SKOP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	verhead line 26066-26115
26111	SK 1	400	3WNDTR	SKOP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	verhead line 26066-26115
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	303.7	101.2	Overhead line 26069-26125
26105	Z.RID	110	26603	TETO-ZR-GT	15	1	100	101.7	101.7	Overhead line 26105-26604
26059	SK 1-A	110	26063	SK 4-A	110	2	123	190.8	171.3	400/110/35 kV Transf. Skopje 5
26062	SK 3	110	26063	SK 4-A	110	2	123	140.2	123.1	400/110/35 kV Transf. Skopje 5
26063	SK 4-A	110	3WNDTR	SKOPJE 4	WND 2	1	300	478.5	159.5	400/110/35 kV Transf. Skopje 5
26064	SK 4	400	3WNDTR	SKOPJE 4	WND 1	1	300	51[illegible].5	170.2	400/110/35 kV Transf. Skopje 5
26059	SK 1-A	110	26063	SK 4-A	110	2	123	119.9	105.3	400/110/35 kV Transf. Skopje 4
26059	SK 1-A	110	3WNDTR	SKOPJE 5	WND 2	1	300	484.8	161.6	400/110/35 kV Transf. Skopje 4
26105	Z.RID	110	26603	TETO-ZR-GT	15	1	100	100.2	100.2	400/110/35 kV Transf. Skopje 4
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	513.5	171.2	400/110/35 kV Transf. Skopje 4
26105	Z.RID	110	26603	TETO-ZR-GT	15	1	100	100.8	100.8	400/110/10 kV Transf. Kumanovo
26111	SK 1	400	3WNDTR	SKOPJE 5	WND 1	1	300	306.9	102.3	400/110/10 kV Transformer Ohrid

Elements with high line loadings after a contingency

Source: DNV GL, Study effects of Plug-in Electric Vehicles (PEV) on the Transmission Grid in Macedonia[17]

Curtailment and re-dispatch

For a given grid situation, overloads or voltage issues may require changes to the dispatch of generation or load, including for instance the curtailment of variable renewable energy (VRE) or re-dispatch of conventional generation. Corresponding measures are of key importance for a comprehensive economic assessment and may have a substantial impact on the wholesale market. For this purpose, Figure 14 presents an example, showing the location and volume of corresponding measures for a given planning scenario for the German transmission grid.

[17] DNV GL Energy Advisory GmbH, "Effects of Plug-In Electric Vehicles (PEV) on the Transmission Grid of North Macedonia (Final Report)," Final Report, April 23, 2019. Available at: https://www.mepso.com.mk/CMS/Content_Data/Dokumenti/%D0%A1%D1%82%D1%83%D0%B4%D0%B8%D0%B8%20%D0%B8%20%D0%B0%D0%BD%D0%B0%D0%BB%D0%B8%D0%B7%D0%B8/2019/MEPSO_PEV%20EN.pdf; last accessed on June 17, 2020

Measure	GW
Curtailment Wind	*-6.8*
Re-dispatch Downward	*-5.5*
Re-dispatch Upward	*+5.3*
Re-dispatch Hydro	*+0.2*
Reserve	*+5.8*
Re-dispatch Abroad	*+1.0*
Sum	***0,0***

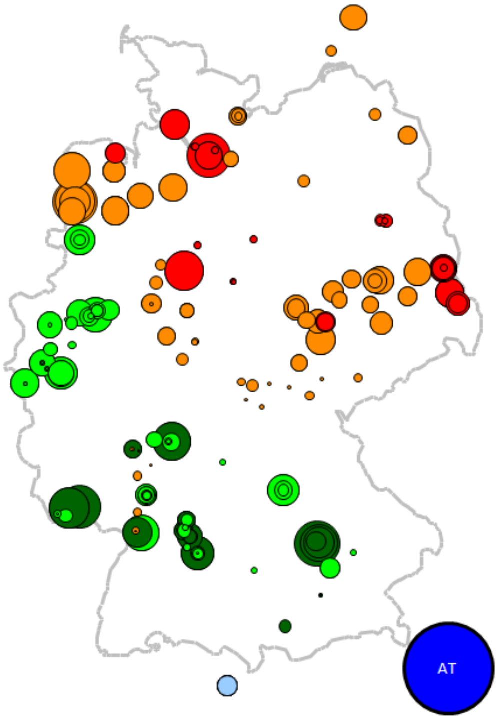


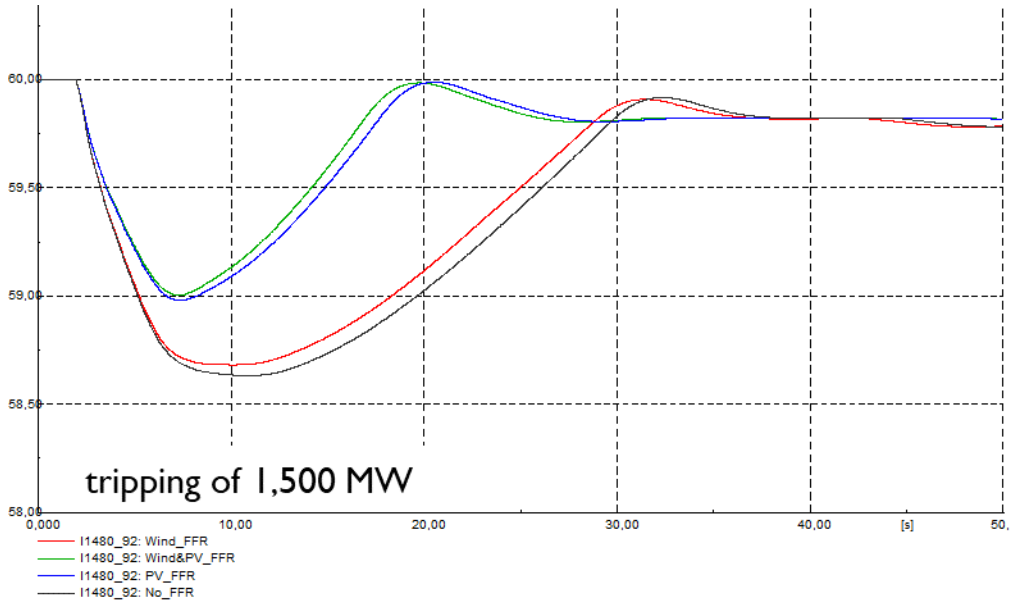
Figure 14: Illustration of VRE curtailment and redispatch needs in Germany

Source: Based on report by the four German TSOs[18]; additional explanations by DNV GL

Visualization of dynamic studies

While dynamic studies may be considered to be of limited relevance for the particular purpose of this primer, they are of key importance with regard to the assessment of possible challenges caused by variable RE. To illustrate this, Figure 15 shows the impact of a generator trip on system frequency. According to this analysis, the trip causes a maximum frequency drop to ~58.70 Hz (against a nominal system frequency of 60 Hz), while the primary reserve is capable of stabilizing the frequency at this level.[19] Additionally, three scenarios with different levels of Fast Frequency Response (FFR) contribution from installed PV and wind farms have been evaluated. Inertia is provided by synchronous generation and affects how quickly frequency drops after a trip. The higher the FFR respectively artificial inertia in the power system, the slower the frequency drop, as shown in the "wind&PV_FFR" scenario. In isolated or smaller interconnected power systems, decreasing system inertia may lead to frequency stability issues.

[18] 50Hertz Transmission GmbH et al., "Abschlussbericht - Systemanalysen 2018."
[19] Please note that this fictive example was calculated without consideration of automatic generation control.



<u>Figure 15: Example of dynamic frequency stability analysis</u>

Source: DNV GL/GridLab

6 Role of the Regulator

The role of the regulator in the modeling process varies from country to country. This chapter gives an indication of possible roles that the regulator can take at different stages during the overall process, i.e.:

- **framing the modeling process**, such as defining the scope of the analysis, roles and responsibilities, key processes, timelines etc.;
- **definition of scenarios and assumptions**, i.e. as required to complete all necessary input data for the analysis (compare sections 3 and 4.1 above);
- **monitoring the scope of load flow studies**, potentially including the identification, elaboration, and analysis of transmission expansion options; and
- **interpretation and approval of results**, including the final approval of the load flow study itself and its further use for regulatory practice.

In the following, we present and comment on each of these stages in more detail.

6.1 Framing the modeling process

Within the boundaries of existing legislation and its remits, one of the main roles of the regulator is to set a framework, which facilitates and standardizes the overall process and defines clear roles, responsibilities, and interactions between different stakeholders. In addition, it is essential that the TSO (and/or other relevant entities) have access to necessary data.

Some of the key tasks, which may be defined and governed by the regulator, include the following:

- *Definition of relevant data and responsibilities*. It should be clear which stakeholders are responsible for collecting and respectively providing which information. An example would be that the operator of a generating unit would have to provide information on technical characteristics and capabilities to the system operator.
- *Process definition*. It is helpful if the entire modeling process is clearly defined, including the initial collection, exchange, and processing of input data, scenario development, modeling, and the final discussion and approval of the modeling results. This includes clear timelines for the key parts of the process. Similarly, a separate process for review, consultation, and approval of key assumptions and/or modeling outcomes should be defined.
- *Facilitate communications and stakeholder engagement*. It must be ensured that the regulations for collecting, preparing, and exchanging the data applies to all relevant stakeholders. These include generators, consumers, network operators, system operators, as well as operators of other relevant assets such as interconnectors and storage facilities.
- *Standardization of tools and templates*. The quality of the modeling process can be improved by clear and unanimous definitions and a standardized data exchange between the TSO and all relevant stakeholders. To this end, the regulator may develop regulations concerning the tools and templates to be used for the monitoring, collection, and exchange of data, and/or monitor and approve the preparation of corresponding rules and instruments by the TSO.

Depending on local legislation and common practices, certain tasks or responsibilities may also be under the authority of the TSO itself. Similarly, the regulator may restrict itself to defining basic rules only, describing the responsibility and key requirements for the transmission expansion planning process, while leaving the elaboration of further details to the TSO. But even in these cases, the regulator has an important role to play, i.e., to monitor the process, confirm that all necessary aspects are addressed, intervene where necessary and, potentially, confirm and/or approve any corresponding proposals or rules developed by the TSO.

6.2 Definition of scenarios and assumptions

While much of the required data can often be collected from different stakeholders, certain inputs will always rely on expert assumptions, or require at least an expert judgement on the range of different data points and sources available. In some cases, these choices may have a decisive influence on the outcome of the load flow studies. Similarly, the definition and selection of scenarios inherently involves discretionary decisions on the focus of the analysis and, equally important, which aspects will be neglected.

In many countries, the corresponding processes are left to the discretion of the TSO and/or other network operators, whereas the regulator is involved in the review of the final development plan only. In contrast, a different approach has been taken in Germany, where the federal regulator organizes a first consultation and decides on the scenario framework proposed by the TSO before any detailed flow studies are started; see Text box 1. While this additional step prolongs the initial process, it allows for stakeholder participation at a much earlier stage and minimizes the risk that the TSOs must re-do their analysis at a later stage.

6.3 Execution of load flow studies

In most countries, load flow studies and all associated analysis are exclusively carried out by the TSOs, possibly in coordination with other network operators and/or owners. This reflects the fact that these parties are not only most familiar with the corresponding networks and have access to the necessary tools and data but would also be responsible for grid expansion at a later stage. Conversely, the regulator should ideally keep a certain 'distance,' as the proposed developments will influence the future costs of the network.

Nevertheless, again in the example of Germany, the federal regulator also contains a department, which is capable of carrying out its own load flow studies and is involved in the detailed planning and analysis of proposed grid development measures. Still, it is important to mention that the decision to assign such competences and responsibilities to the regulator is not related to the regulator's basic functions for the oversight of the electricity market. Instead, it is linked to the regulator's specific role in the detailed planning of major grid expansion measures in the context of the so-called Federal Requirements Plan (FRP) and the Federal Sectoral Planning process (compare Text box 1), which were implemented in an attempt to streamline and accelerate the planning process.

Text box 1: Role of German regulator in transmission expansion planning[20]

The federal German energy regulator, the Bundesnetzagentur[21] or BNetzA, has several key responsibilities within the process for transmission expansion planning. Starting from the review and approval of the **scenario framework** developed by the TSOs, the BNetzA is also responsible for approval of the final **network development plan** and several subsequent steps for detailed planning of certain projects.

Item	Role of BNetzA
Scenario Framework	The four German TSOs develop a scenario framework describing different generation expansion scenarios. The framework is subject to review, consultation, possible modifications and approval by the BNetzA.
Network Development Plan	Based on the approved scenario framework, the TSOs carry out load flow studies and prepare the draft network development plan for the next decade. Similar to the scenario framework, the BNetzA is responsible for review, consultation, and approval of the network development plan. In addition, it also carries out a high-level environmental impact assessment (EIA).
Federal Requirements Plan	At least once in four years, the BNetzA prepares the Federal Requirements Plan (FRP) and submits it to the Federal government for approval. The FRP is based on the Network Development Plan and the associated EIA and specifies all necessary projects.
Federal Sectoral Planning	For lines included in the Federal Requirements Plan Act, which cross state or national borders, the BNetzA determines route corridors by means of the so-called Federal Sectoral Planning process.
Detailed routing and planning approval	The exact route of a new line within the defined corridor is determined through the Planning Approval Procedure.

6.4 Interpretation and approval of results

While the role of the regulator during the initial stages of the transmission planning process varies widely, the regulator generally has the right to review and approve the final network development plan. Within the EU, this responsibility was firmly enshrined in the so-called 'Third Package.'

As part of these responsibilities, regulators should normally provide for sufficient consultation with relevant stakeholders, i.e., either by carrying out the consultation process themselves or by accompanying and monitoring the corresponding process conducted by the TSO (or a similar entity).

In addition, the regulator should be capable of conducting a proper review and assessment of the (draft) network development plan and any proposed network expansion measures. In line with the

[20] "Netzausbau - Five Steps," accessed May 7, 2020, https://www.netzausbau.de/EN/5steps/en.html.
[21] Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway

scope of this document, this should include the capability to understand the basic principles of load flow tools and studies, being able to interpret the modeling outcomes and understanding the impact of important inputs on load flows and network operation.

To support this process, it is furthermore desirable that the regulator is not only entitled to ask general questions, but also to request an assessment of specific changes to input assumptions, scenarios, and/or expansion measures, even if this may require additional load flow studies. Where necessary, this should also include the right to extend the overall deadline of the planning process, at least within reasonable limits.

This approach is reflected for instance by the overall process for preparation of the transmission grid development plan in Spain, as summarized in Text box 2 below. Although the corresponding functions are carried out by the Ministry of Ecological Transition rather than the regulator, the overall process provides for an additional iteration after preparation of the first draft of the plan. More specifically, the first draft is consulted with relevant authorities, in order to identify specific questions and needs for changes. Any feedback must then be addressed by the TSO in the second study phase, before the updated development plan is submitted for public consultation and, eventually, final approval by the government.

Text box 2: Transmission grid planning process in Spain[22]

The Spanish transmission expansion plan defines the planned development of the electricity transmission grid for the next six years. The primary objective of the expansion plan is to ensure security of supply While facilitating the energy transition. In addition, it must comply with the energy policy defined at the national and European level.

The planning process is structured into the following six phases.

Item	**Roles and responsibilities**
Phase 1: Proposal phase (3 months) *Participants: Ministry, Autonomous Communities, Market agents, Regulator (CNMC)*	The Ministry for Ecological Transition publishes the start of the planning process in the Official Gazette of the Spanish State. Afterwards, the autonomous communities and other actors prepare transmission grid development proposals and send them to the Ministry and the TSO (REE). In parallel, the regulator (CNMC) prepares a report defining financial and economic sustainability criteria that should be taken into account when developing the network development plan.
Phase 2: Study phase (6 months) *Participants: TSO (REE)*	Based on the information it has received, REE conducts the necessary technical studies, prepares the initial development report, and sends it to the Ministry.
Phase 3: Debate phase (1 month) *Participants: Ministry, Autonomous Communities*	The Ministry consults the initial development proposal with the autonomous communities and prepares a consolidated response to the TSO.
Phase 4: Studies phase (2 months) *Participants: Ministry, TSO (REE)*	Based on the feedback received, REE updates the development plan and sends it back to the Ministry.
Phase 5: Consolidation phase (4 months) *Participants: Ministry, TSO (REE), Regulator (CNMC), Public*	CNMC assesses the compliance of the development plan with sustainability criteria and gives its opinion to the Ministry. The Ministry prepares the final transmission grid development plan, which must include a strategic environmental declaration issued by the Ministry's environmental office. Stakeholders may comment on this plan during a public consultation period.
Phase 6: Approval phase *Participants: Government, Congress*	The final transmission grid development plan is approved by the government once it has been passed by congress.

22 “Red Eléctrica de España | The 2021-2026 Planning Process,” accessed May 7, 2020, https://www.ree.es/en/activities/electrical-planning/new-transmission-grid-planning.

7 Concluding Remarks

This primer has provided an overview of the application of load flow studies in the context of energy regulation, i.e., transmission planning and assessment of changes to market design. Corresponding studies are usually carried out by network operators, such as TSOs or DSOs, while energy regulators are not usually directly involved themselves. Nevertheless, in order to ensure an objective and transparent approach, facilitate stakeholder engagement and be able to properly assess the outcomes, it is paramount that regulators are aware of the fundamental principles of load flow studies, relevant inputs and outputs, and appropriate tools and approaches for interpretation and further results of the results.

Besides commonly available industry standard tools, such as PSS®E, PowerFactory, NEPLAN or Powerworld, network operators may also rely on other, sometimes local software packages for load flow studies. Despite significant differences with regards to structure and design, available interfaces, and detailed functionalities, most of these tools support a basic set of features for both steady state and dynamic analysis. Consequently, it generally seems appropriate to leave the choice of specific software packages to the discretion of network operators.

In contrast, the outcome of load flow studies crucially depends on input assumptions being used and the detailed scope of the analysis. For this reason, energy regulators need to pay attention to the definition of scenarios and inputs assumptions, data sources and the process for collecting relevant inputs from stakeholders where applicable. This applies in particular to assumptions on the volume and spatial distribution of generation and load, the choice of possible network reinforcements or extensions, the selection of critical branches and contingencies, or the definition of applicable limits and thresholds.

Energy regulators should not aim at conducting this analysis themselves. Yet, they need to be capable of understanding and interpreting typical outputs, such as loadings of (critical) grid elements or voltage profiles. Again, the key focus should be on understanding the relation between such outputs, on the one hand, and the resulting impact on system and network security, on the other hand.

In line with these considerations, energy regulators should aim to focus on the following tasks in the context of load flow studies for transmission planning and market design changes:

- **framing the modeling process**, such as defining the scope of the analysis, roles and responsibilities, key processes, timelines etc.;
- **definition of scenarios and assumptions**, i.e., as required to complete all necessary input data for the analysis (compare sections 3 and 4.1 above);
- **monitoring the scope of load flow studies**, potentially including the identification, elaboration, and analysis of transmission expansion options; and
- **interpretation and approval of results**, including the final approval of the load flow study itself and its further use for regulatory practice.

It is recommended that regulators take a proactive and cooperative approach, being involved in the planning process from an early stage, incl. the development of scenarios before any load flow analysis is carried out, and that they focus on ensuring proper coordination between TSOs and DSOs for the overall planning process.

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