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Systems Analysis of Electricity Transmission Networks for Improved Sustainability

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The key function of an electricity transmission network is to transfer electrical energy from generators and imports to all customers reliably, at low cost, and sustainably as far as possible. The regional or country-level networks are usually highly interconnected with a large number of nodes and redundant subnetworks. Various types of power plants provide energy for the network. They are mainly nuclear-, fossil- or renewables-based. The power generation technologies have different availabilities, costs, and sustainability indicators. In the present work, the systems analysis of electricity transmission networks is performed, based on the cost, the availability and sustainability indicators. The P-graph framework has been used, where all feasible structural options are enumerated. Naturally, these indicators are inter-dependent; for example, increasing the share of renewables in the overall energy supply for better sustainability may reduce the availability of the system. On the basis of the current work, the sustainability of the transmission network can be maximised without compromising the overall availability. Hungary's electricity transmission network has been examined to illustrate the proposed procedure.

1. Introduction

There are two types of electricity networks (Ziad, 2013): transmission and distribution. A transmission network transports a large amount of electricity over long distances via high-voltage electric transmission lines from the various power plants to distribution networks through its substations. A distribution network transfers energy locally from the transmission network to the customers via middle- or low-voltage electric distribution lines. A substation may connect transmission lines of both types of networks, power plants, and may alter the voltage between the connected transmission lines. While the transmission networks have a grid structure with redundancy, including loops, distribution networks have tree structure without redundancy in most cases.

The availability of a transmission network is the fraction of the time when it is operational. A transmission network is considered operational if it is capable of transferring energy to all distribution networks on the required level at any time. In transmission networks, the usual requirement related to availability is the so-called N-1 criterion (Hemmati et al., 2013). It states that an unexpected outage of a single system component of the transmission network (e.g., transmission line, power generation plant) must not result in a loss of load to any distribution network. Therefore, in case of the failure of any component of the transmission network, the network is still able to accommodate all flows to all distribution networks at the required level. Even though "criterion N-1" is considered as a severe requirement, it does not provide information on the availability of the system as far as it is considered in Process Systems Engineering (PSE).

Transmission Network Planning (TNP) has been well established as a research topic, as can be seen from the comprehensive review in (Hemmati et al., 2013), establishing the lack of unified methodologies for TNP and for accounting for the introduction of renewables. In that work, the various reliability considerations are discussed. Van der Weijde and Hobbs (2012) analysed the economic implications of increasing the share of renewables and the related risks of neglecting the uncertainty introduced by this arrangement.

Ruiz and Conejo (2015) analysed transmission expansion planning under uncertainty, also considering possible demand growth in the future. A recent review (Collins et al., 2017) focuses on the issues of building into the models of short-term variations in the power systems. It discusses the problems of integrating renewable energy sources and network reliability, but without making an explicit link among them. In the course of the state of the

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art analysis, no study was found on enumeration-type analysis. To fill the gap, in the current work, transmission networks have been examined for their availability and sustainability in relation to the increased use of renewables, by the methodology of PSE. An enumeration type availability analysis of processing systems has been adapted to transmission networks.

2. Problem statement

The transmission network is specified by the network of transmission lines, substations, and power plants. A transmission line is given by its two nodes, its voltage, and the maximum power that can be transferred from its nodes. A transmission line can be unidirectional or bidirectional. A power plant is specified by its maximum available power, furthermore, the time-dependent power profile on the date of the year and time of the day. The power profile for coal, hydrocarbon, and nuclear power plants are supposed to be constant and varying for renewables. The required energy output from the transmission network is given by the demand of the connected distribution networks under their own time-dependent profile. Each element of the transmission network has an availability indicator. The availability of the electricity transmission network is determined as the probability that the transmission network transfers the required energy to the distribution networks on the required level at any time. The availability of the Hungarian electricity system has been analysed for different cases where the energy demand and the share of the renewable energy generation are varied.

3. Proposed methods

3.1 P-graph framework

The P-graph framework has been initially developed for chemical Process Network Synthesis (PNS), where these type of problems are specified by the sets of desired products (targets), available raw materials (resources), and candidate operating units (building blocks) of the process to be synthesized. The process networks are represented by directed bipartite graphs, the so-called P-graph. The framework is based on a set of axioms expressing the fundamental combinatorial (structural) properties of feasible process networks (Friedler et al. 1992a), i.e., the search for the optimal or n-best processes can be reduced to the set of process networks satisfying these axioms resulting in a massive acceleration in the search. There are several P-graph algorithms, e.g., for generating all feasible process networks and the n-best process networks (where “n” is a specified count) together with their optimal parameter settings (Friedler et al. 1992b).

3.2 Availability analysis based on P-graph framework

The availability of a process is defined as the ratio of the time that the process is capable of performing its determined tasks at a sufficient level. For determining the availability of a complex process, a P-graph based reliability analysis tool (Kovács et al. 2018) has been adopted as far as it has been done in Orosz et al. (2018) for availability analysis. The availability *A* of a process is determined as the sum of the probabilities of all of its operational sub-processes based on the formula in Eq(1)

$$A = \sum_{(x_1, x_2, \dots, x_k) \in U} \prod_{i=1}^{k} {p_i}^{x_i} (1 - p_i)^{(1-x_i)} \quad (1)$$

where set U collects the networks of all operational sub-processes in the form of binary k-vectors (x_1, x_2, …, x_k). If an operating unit is in the network of a sub-process, the related binary variable is set 1, otherwise 0. The availabilities of the operating units are given by p_1, p_2, …, p_k.

4. Case study

The availability of the Hungarian transmission system has been analysed; its network is given in Figure 1. The highly interconnected network contains the high voltage power lines of 750, 400 and 220 kV, the substations, and the main power plants. The transmission network has connections to the distribution networks; these connections are not shown in Figure 1. The power plants have different types of power generation technologies; these are nuclear, fossils or renewables based. These technologies have different availabilities, costs, and sustainability indicators. The data of the power plants (31 December 2017) are summarized in Table 1. The current capacities of the power plants are considered in the availability analysis. Stand-by plants with zero or small capacity factors are also listed in Table 1.

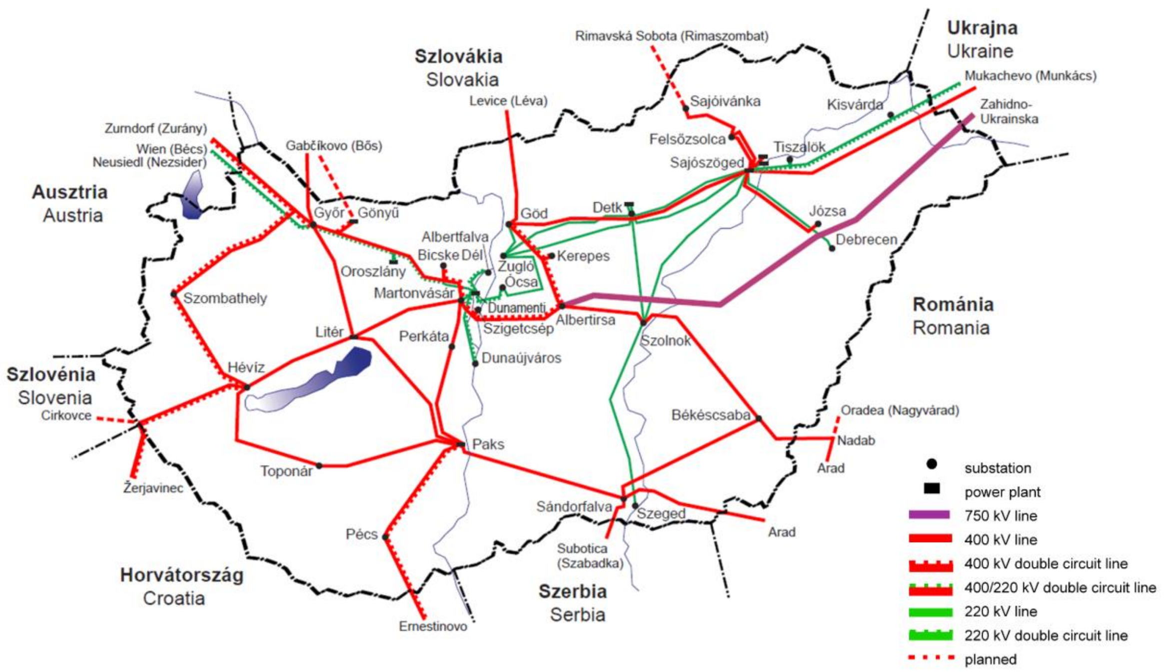


Figure 1: Hungarian transmission network (MAVIR, 2019a)

Table 1: Hungarian power plants over 50 MW (from MAVIR, 2019a)

Power plant	Energy source	Gross installed capacity [MW]	Current capacity [MW]	Capacity factor [%]	Power plant	Energy source	Gross installed capacity [MW]	Current capacity [MW]	Capacity factor [%]
Paks	nuclear	2,000	2,000	91.9	Kelenföld	hydrocarbon	127.9	127.9	30.3
Tisza II.	hydrocarbon	900	0	0	Vértesi	coal+biomass	240	0	0
Dunamenti I.II.	hydrocarbon	386	386	6.4	Litér GT	hydrocarbon	120	120	0.5
Gönyű	hydrocarbon	433	433	55.2	Lőrinci GT	hydrocarbon	170	170	0.3
Csepel	hydrocarbon	292	282	14.6	Sajószöged	hydrocarbon	120	120	0.5
Mátra I. II. GT	lignit+biomass	950	920	64.2	Debrecen	hydrocarbon	95	0	0
Dunamenti III.	hydrocarbon	407.7	407.7	39.1	Bakony GT	hydrocarbon	116	116	4.0
Újpest	hydrocarbon	105.3	105.3	52.5	Ajka	coal+biomass	101.6	48	18.0
Kispest	hydrocarbon	113.3	113.3	41.3	Pécs	biomass	70	35	36.5

The P-graph representation of the Hungarian transmission network is given in Figure 2, where power plants, transmission lines, and distribution networks are represented by operating unit type nodes of P-graph shown as horizontal bars. A distribution network is defined by its time-dependent consumption. A substation is given as a material type node of a P-graph shown as a small circle. The energy sources to and consumptions from the transmission network are given as “raw materials” and “products” in the P-graph representation. The network contains 54 bidirectional transmission lines (including 23 double lines), 22 power plants, 30 substations, and connections to 27 distribution networks.

The total electricity consumption of Hungary was 45,460 GWh in 2017. The production of domestic power plants was 32,584 GWh, and that of the import-export balance was 12,876 GWh. The electricity consumption of end users was 39,252 GWh, and the self-contribution of power plants and the network losses were 2,067 and 4,141 GWh (MAVIR 2019a, MAVIR2019b).

For determining the availability of the transmission network, it is supposed that the availability of any power plant and any transmission line are 0.995 and 0.999. According to formula Eq(1), the availability of the transmission network is 0.9859, where the number of the functional subnetworks is 55.867.

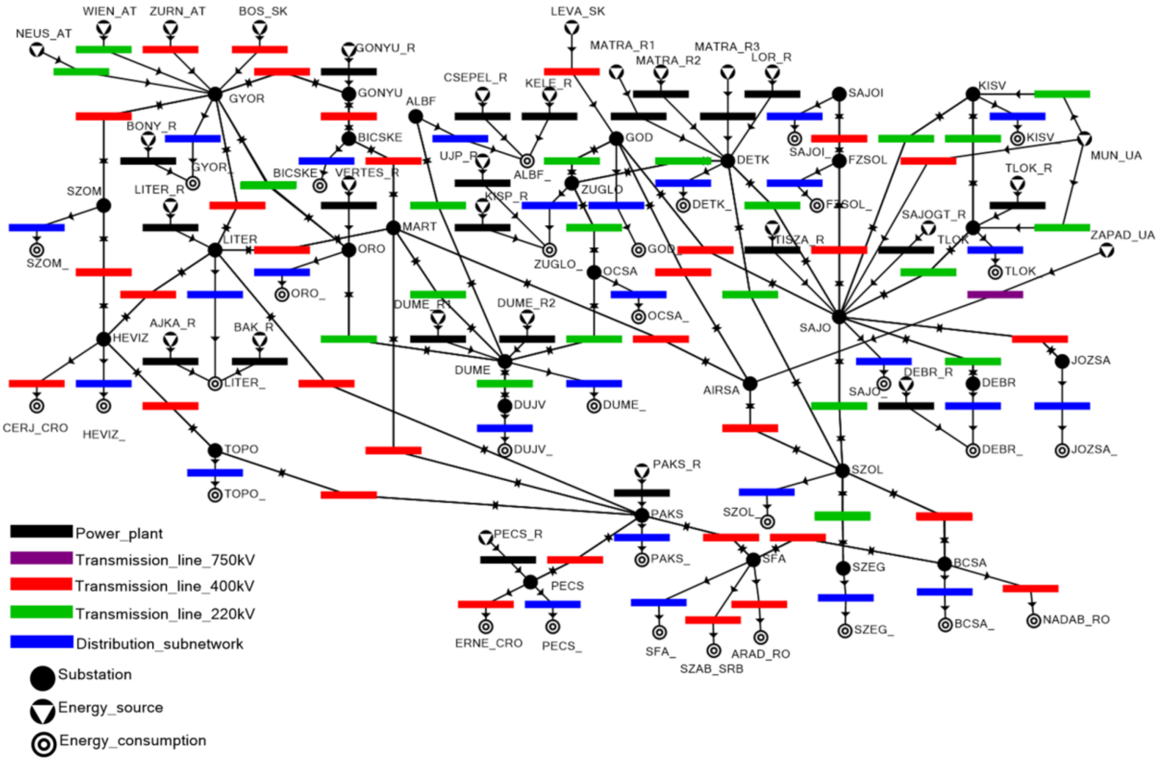
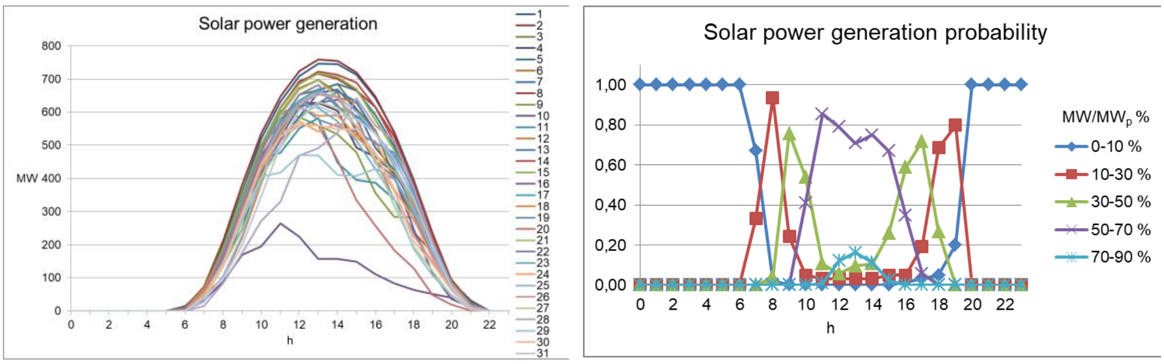


Figure 2: The P-graph representation of the Hungarian transmission network

According to the National Energy Strategy of Hungary (NES, 2012), the long-term sustainability and security of energy supply in Hungary have to be ensured. An important pillar is the increasing use of renewable energy. In the Hungarian electricity system, the installed capacity of photovoltaic (PV) generators was 314.42 MW in 2017. In the coming years, a significant increase in the capacity of PV generators is expected by on-going and planned investments of nearly 1,000 MW PV generators, furthermore, by the spread of PV microgeneration plants for households (MAVIR, 2017a). Based on these facts, the effect of solar power generation on the overall system is increasing, so further investigation deals with the effect of solar power generation growth to the system availability.

Besides the advantages of photovoltaic generators, the unpredictability of solar energy reduces the availability of the energy system. The characteristics of solar power generation of 1,000 MW_p solar power capacity based on historical solar photovoltaic power data (Elia, 2019) in July 2018 is shown in Figure 3a. It can be seen that the generated power before 6:00 am and after 9:00 pm is zero. According to these data, the hourly probability of supplied power at different intervals of MW/MW_p is shown in Figure 3b.



(a) (b)

Figure 3: (a) Solar power generation of 1,000 MW_p PV capacity. (b) Solar power generation probability

In the availability analysis of the Hungarian transmission network, it is supposed that the energy demand is increased by 20 % compared to the July 2018 data. In this analysis, both photovoltaic and non-renewable power generators have been added to the transmission network with different levels of power generations. The availabilities of the transmission network with different cases have been determined by formula Eq(1).
The hour-by-hour variation of the total consumption, the production of domestic power plants and the import-export balance of the Hungarian electricity network in four different days of July in 2018 are shown on Figure 4 (MAVIR, 2019b). It can be seen, that the shape of the hourly profiles of the total consumption and the import-export balance are similar, the import-export balance follows the change of the demand in time and the power plant generation more or less constant. According to these data, the transmission network availability has been determined for 20 % consumption profile increasing, unchanged import-export balance profile, and various increase of power plant capacity with renewable and non-renewable energy sources. Photovoltaic power generation is considered here as renewable power generation.

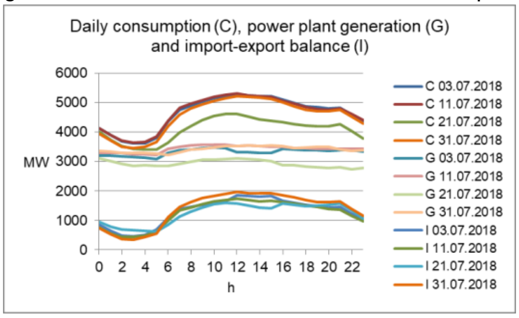


Figure 4: Daily total consumption, power plant generation, and import-export balance in Hungary in 2018

The system availability with 20 % consumption growth and different amount of power generation growth generated by renewable and non-renewable energy sources is summarized in Table 2 and Figure 5. The 0.9880 availability of the original transmission network is slightly reduced if the growth of the consumption is compensated by an equivalent level of non-renewable energy sources expansion; see line 1 of Table 2. This is partly because of the capacity limits of the transmission network. If the growth of energy demand is only partly served by continuously available non-renewable power generation growth, the minimum availability of the transmission network is reduced, independently of the amount of additional renewable power generation maximum capacity.

Table 2: System availability (1), at 20 % consumption growth

Power generation growth rate [%]		Time of the day [h]											
Renew-able	Non-renew-able	0	2	4	6	8	10	12	14	16	18	20	22
0	20	0.9880	0.9880	0.9880	0.9880	0.9880	**0.9879**	**0.9879**	**0.9879**	0.9880	0.9880	0.9880	0.9880
10	0	0.9809	0.9858	0.9859	0.9810	0.9808	**0.9803**	0.9810	0.9810	0.9854	0.9823	0.9809	0.9808
10	5	0.9877	0.9879	0.9879	0.9879	0.9876	**0.9875**	0.9876	0.9876	0.9879	0.9879	0.9877	0.9877
10	10	**0.9879**	0.9880	0.9880	**0.9879**	**0.9879**	**0.9879**	**0.9879**	**0.9879**	0.9880	**0.9879**	**0.9879**	**0.9879**
10	20	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**
20	0	0.9809	0.9858	0.9859	0.9810	0.9811	0.9856	0.9856	0.9857	0.9858	0.9856	**0.9809**	**0.9808**
20	5	**0.9877**	0.9879	0.9879	0.9879	0.9878	0.9879	0.9878	0.9878	0.9880	0.9879	**0.9877**	**0.9877**
20	10	**0.9879**	0.9880	0.9880	**0.9879**	**0.9879**	0.9880	0.9880	0.9880	0.9880	0.9880	**0.9879**	**0.9879**
20	20	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**
30	0	0.9809	0.9858	0.9859	0.9810	0.9856	0.9859	0.9858	0.9858	0.9859	0.9857	0.9809	**0.9808**
30	5	**0.9877**	0.9879	0.9879	0.9879	0.9879	0.9880	0.9880	0.9880	0.9880	0.9880	0.9878	**0.9877**
30	10	**0.9879**	0.9880	0.9880	**0.9879**	0.9880	0.9880	0.9886	0.9885	0.9880	0.9880	**0.9879**	**0.9879**
30	20	**0.9880**	**0.9880**	**0.9880**	**0.9880**	**0.9880**	0.9899	0.9924	0.9921	0.9924	**0.9880**	**0.9880**	**0.9880**

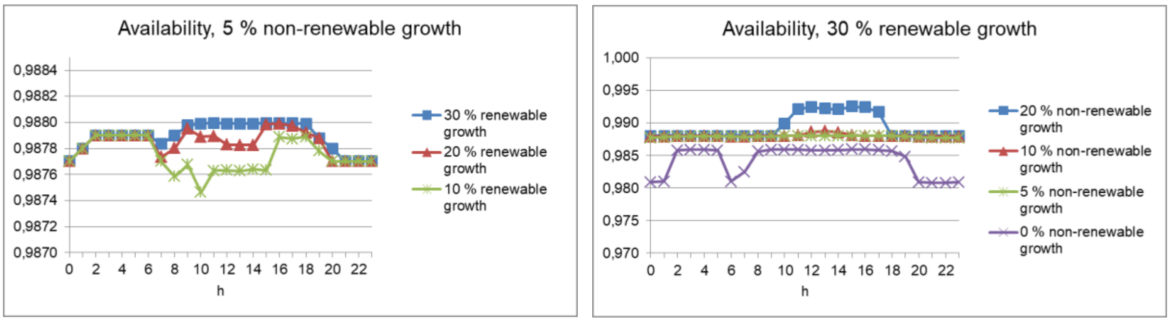


Figure 5: System availability with 20 % consumption growth and with different amount and type of power plant capacity growth

5. Conclusions

The availability of electric transmission networks has been analysed by an enumeration type availability analysis tool developed for process systems engineering (PSE). It has been shown that raising the participation of renewable power generation may reduce the availability of the transmission network. If the increasing power demand in the coming years is totally assured by photovoltaic power generation, the availability of the system may become unacceptably low. Consequently, the ratio of the renewables in the total power generation is a key parameter of the development of transmission networks if the availability is specified. The current work illustrates that PSE tools can successfully be applied in transmission networks. However, the consequences highly depend on the selected network and its parameters.

Acknowledgements

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