ON COMPETITIVENESS OF POWER SYSTEMS IN TECHNOLOGY TRANSITION

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Abstract: Power systems technology transition is defined as the process of changing the systems technology structure until a new technology becomes dominant in the electricity generation. Evaluation of a power system's competitiveness in technology transition is considered. For the competitiveness metrics is used $3E_{\mathrm{TT}}$ Indicator. General approach is demonstrated on the hypothetical power system consisting of five different energy technologies, i.e. wind turbines, nuclear power plants, lignite fired and hard coal fired power plants, as well as combined cycle gas turbines. Sensitivity analysis to cost ratio changes is also performed and corresponding results are presented. Regarding ability of a power system to change the power on demand the power system's competitiveness is analyzed using dispatchability and ATC Indicators. Obtained results are presented and discussed. The results point out that better competitiveness of the power system can be reached with technology transition from hard coal and lignite fired technologies to nuclear technology than with the transition from hard coal and lignite-fired technologies to wind turbines technology.

Key words: Technology transition, Competitiveness, Energy technology, Technology portfolio, Power system

1. INTRODUCTION AND PROBLEM DEFINITION

Energy transition was the subject of many scientist's interest as it is presented in [1]. Energy transition is generally treated as transition from one kind of primary energy to the other. So in [2] are distinguished three energy transitions, i.e. from biomass to coal, from coal to liquid fuel and from liquid fuel (and coal) to natural gas. Thereby comparatively higher economic efficiency of the new fuels were the drivers in these transitions. According to [1] nowadays is beginning transition from fossil fuels to low-carbon energy sources so called the fourth energy transition, driven with quite different drivers.

In above division on energy transitions, however, cannot be seen the great transition, performed in the twentieth century, from low generating capacities on steam cycle based power plants of about 10MW and low efficiencies of about 10% to extremely high capacities of about 1500MW and high efficiencies of about 45%. In fact, there are some significant specificities of technology transitions in general, especially in power systems technology transition and some of them will be treated in this paper.

Notation technology transition of a power system is connected to the technology system that comprise technology portfolio for electricity generation, electricity transmission system, distribution and consumption systems. In principle a technology transition of a power system can be defined as a process when the investments in new technology assets are made deliberately regardless that existing assets can provide enough electricity for the market, with final consequence that new technology becomes dominant in the electricity generation. In past, two technology transitions of power systems can be distinguished. First one was the pass from hydro power plants to fossil-fueled thermal power plants with steam cycle. As a rule, this technology transition is followed by strong increase in electricity demand, and therefore, hydro power plants generally remained in operation deeply into developed the transition process. In single countries, like Norway, hydro power plants are still predominant technology for electricity generation. Second technology transition of power systems occurred during a long period of time when new steel processing technologies, new alloys and new equipment designs enabled significant increase of power plant’s efficiency, as well as the improvements of the fossil-fueled thermal steam power plants performance characteristics. Within the second technology transition two new specific technology lines were also successfully developed, i.e. nuclear power plants and gas turbines including combined cycle gas turbines (CCGTs). Although in these technology lines are reached significant development expressed through high energy densities, neither of them become dominant in electricity generation.

The driving foresees of both technology transitions were economic, as well as the operation benefits for the power systems owners. Important characteristic of the both technology transitions is that they occurred in developing period of the power system’s life characterized with more or less strong increase in electricity consumption. In such circumstances, economic gain with the new technology was always higher than the loss due to withdrawal from operation the equipment technically capable for further operation, and which yet has not been written-off, but with lower efficiency and lower performance characteristics than the new ones.

In the past development of these two energy transitions also can be distinguished periods with very slow transition processes and even with no transition process. Important characteristic of such periods is that new electricity generating capacities that had to be put in operation were generally equal or almost equal to the old capacities that had to be pulled out of operation plus the capacities that were necessary to cover increase of the electricity consumption. In this sense, new capacities can be considered as the capacities for maintaining certain equilibrium state of the power system technology development. The consequence of the equilibrium is that there are no addition excess capacities over previously estimated consumption needs with the necessary reserve capacities. It also means that there are no additional investments in the assets over the level that is determined by the technological and performance needs.

Contemporary power systems in developed countries are at the doorsteps of another technology transition. For the transition, the driving force is state's request to minimize CO_2 emission during electricity generation. The request is supported by prescribing priority in-feed of CO_2 free electricity, higher price of electricity generated by CO_2 free technologies compared to the electricity generated by CO_2 dependent technologies, and additional taxes on CO_2 emission from CO_2 dependent technologies. New capacities for CO_2 free electricity have to be built primarily in order to satisfy external request in the form of state's laws for reduction of the emission. Obviously, in such technology transition the power system has excess generating capacities related to the electricity consumption needs. However, these capacities do not satisfy the established request of the higher order, since they are able to generate CO_2 dependent electricity only. Simultaneously, the cost of the additional asset that can generate electricity in accordance to the needs has to be treated as an additional cost related to the technology transition needs.

2. COSTS OCCURRING IN A POWER SYSTEM'S TECHNOLOGY TRANSITION

Several costs are close conditioned by a power system's technology transition. The costs are: 1) investments in existing technologies that are producing electricity in residual load domain (if the system already has some i-RES technologies with priority in-feed). 2) Investments in new CO_2 free technologies. 3) Additional investments that are not directly connected with electricity generation. This category comprises necessary system costs like additional investments in electricity transmission and distribution networks, as well as other extra costs like compensation for loss of workplaces and other cost formed at the social level. The cost that occurs when existing technology portfolio is unable to change the power on demand is not covered here and it should be estimated separately in accordance with capability of the technology portfolio to change its power on demand. All at all the transition costs seem to be larger as more as the transition process is faster or greater in the scope.

The investment cost of the written-off equipment during technology transition has to be subtracted from the sum of the three costs over mentioned.

3. INDICATING COMPETITIVENESS OF POWER SYSTEMS TECHNOLOGY TRANSITION

Literature survey shows existence of the interest in defining the indicators aimed to indicate energy, economy and environment features of electricity generating technologies. The clean coal technology assessment using 3E analytic method and logical model of "application-reaction-description" is considered in [3]. In [4] is presented a mathematical model based on the variations of uncertain factors for support of decision-making. The specific procedure for realization of the comprehensive balance and coordinated development among energy, economy and environment is considered in [5]. The goal is to obtain the lowest cost of the technology for carbon emission reduction. In [6] is presented a new methodology for constructing a set of indicators together with identification certain limitations in the methods. The simulation tool for modeling wind power and its unpredictability is presented in [7]. The tool allows determining the effects that wind power has on electricity generation and CO_2 emissions and thus enable analysis of wind speed forecasting accuracy on reliability. In [8] are suggested three indicators to be used as an entity for evaluation different project variants or development scenarios in terms of carbon dioxide emissions. In [9] is proposed a set of four indicators to analyze the impact of carbon dioxide generation and emissions on the profitability of energy technologies, as well as to quantify the effects of the European transmission system on electricity business. In [10] is introduced an approach to ecology, economy and energy evaluation of electricity generating technologies using 3*E* Indicator. In [11] is presented detailed evaluation of electricity generating system's technology mix using 3*E* Indicator.

Coming up from the concept of 3*E* Indicator given in [10, 11], the indicator for competitiveness metric of a power system in technology transition can be expressed with following equation:

$$3E_{TT} = \frac{\left(F_{c0} + F_{cetr} + F_{catr} - F_{cwt}\right)\cdot\left(M_{CO20} + \Delta M_{CO2tr}\right)}{\left(E_0 + \Delta E_{tr}\right)} \tag{1}$$

In eq. (1) F_{c0} denotes annual amount of fix cost (expressed in millions of euro per year) just before starting observed technology transition process. With F_{cetr} is denoted annual amount of added fix cost (expressed in millions of euro per year) for technology transition in electricity generation. With F_{catr} is denoted annual amount of added fix cost (expressed in millions of euro per year) for other non-electricity generation purposes (like electricity transmission and distribution network, compensation for loss of workplaces, etc.) within the technology transition, while F_{coft} corresponds to the equipment with expired operation life, i.e., written-off assets. With ΔM_{CO2} and ΔE_{tr} are denoted changes in annual amount of CO_2 emission (in thousand tons per year) and changes in annual electricity generation (in MWh per year) that occur in the technology transition.

After appropriate ordering, we can write final equation for $3E_{TT}$ Indicator in the form:

$$3E_{TT} = 3E_0 \cdot \frac{\left(1+f_{ct}+a_{ct}-w_{ct}\right)\cdot\left(1-m_{CO2tr}\right)}{\left(1+e_{tr}\right)} \tag{2}$$

With $3E_0$ in Eq. (2) is denoted 3*E* Indicator as defined in [10] and [11] for the power system just before beginning of the technology transition. Symbol f_{ct}, represents the ratio of summarized value of new added assets annual fix cost for each year within the time interval and the annual amount of assets fix cost in equilibrium state just before beginning of the transition. Symbol a_{ct} represents the ratio of summarized value of the cost for other non-electricity generation purposes for each year within the time interval and the annual amount of fix cost in equilibrium state. Symbol w_{ct} represents the ratio of written-off assets cost for each year within the time interval and the annual amount of fix cost in equilibrium state. Symbol m_{CO2tr}, represents the ratio of CO_2 emission reduction and the emission just before beginning of the technology transition, while symbol e_{tr} represents the ratio of the increase of the electricity generation and the generation just before beginning of the technology transition. Equation (2) can be considered as the product of two factors. First, ($3E_0$) represents 3*E* Indicator at the beginning of the technology transition, while the second one corresponds to the changes that occur during the technology transition.

4. ANALYSIS AND RESULTS

In the current research, the goals are to include into the competitiveness analysis the cost of the power system's technology transition, as well as corresponding reduction of CO_2 emission, on one hand and power system's capability to change the power on demand, on the other hand.

4.1. *Cost of technology transition and reduction of CO_2 emission*

For the general analyses is considered the hypothetical power system's portfolio that consists of altogether five different technologies. Wind turbines with priority in-feed are foreseen as representative of i-RES. In the basic part of the residual load domain are foreseen lignite fired power plants (LfPP) and nuclear power plants (NE), hard coal fired power plants (HCfPP) are foreseen in intermediate part, while natural gas fired combined cycle gas turbines (CCGT) are foreseen in the pick part of the residual load domain.

In the previous research [10-13], the analyses were based on the probabilistic approach using power system's load duration curves. The consequence of this approach is that an increase in electricity generation by i-RES with priority in-feed causes the reduction of electricity generation of all other plants that operate in residual load domain including CCGTs. Although theoretically the most adequate, this approach doesn't allow to consider separate transition from only hard coal and lignite fired technologies to i-RES ones. Therefore, in order to present effects of the substitution of hard coal and lignite-fired technologies with wind turbines the deterministic approach is applied. The approach considers calculation of wind turbine capacities necessary to replace certain lignite or hard coal capacities based on estimated wind turbine's time operation of 2500h/a at full power. The analytical model for the analysis is developed based on above considerations. For the case of technology transition from lignite and hard coal to nuclear power plants the results obtained by both methods, i.e. probabilistic and deterministic are presented in Fig. 1. It can be seen that in certain domains of the hypothetical power system's portfolio structure (defined with λ^* and μ_{NE}) the deterministic method gives somewhat smaller values of $3E_{TT}$ Indicator, while in other domains this method gives somewhat higher values, compared to the probabilistic method.

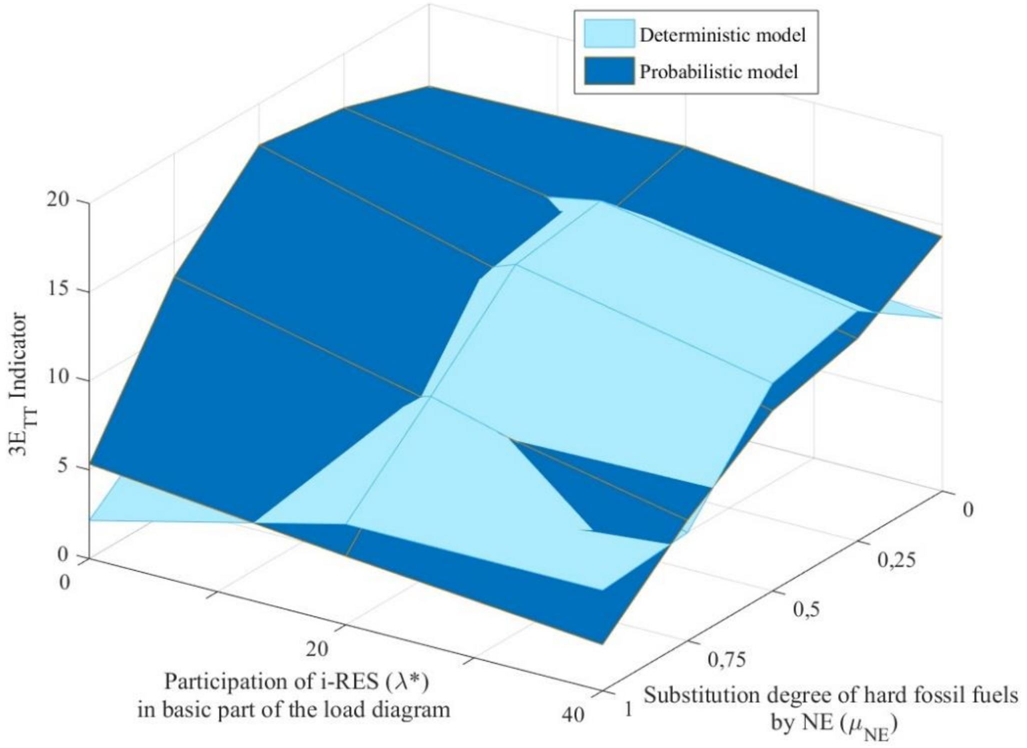

Fig. 1. Comparison of probabilistic and deterministic approach

With symbol μ is denoted the fraction of hard coal and lignite fired technologies that are substituted by CO_2-free technologies as an independent variable. Second variable is the share of electricity generated by NPPs in the basic part of the residual load domain, denoted with β^* (in the case of hard coal and lignite fired technologies substituted by i-RES). In the case of hard coal and lignite fired technologies substituted by NEs, second variable is the share of electricity generated by i-RES in the basic part of the residual load domain, denoted with λ^*. In the analysis are used the same energy characteristics of the considered technologies as those used in reference [11]. Asset's costs that are used in the analysis correspond to prices in 2016, according to [14, 15]. The average values of CO_2 generation per unit of fuel energy for different fuels are calculated using data from reference [16].

It is hard to give a general estimate of the necessary system costs that comprise additional investments in electricity transmission and distribution networks, as well as other extra costs like the cost of closing the coalmines and related compensation for loss of workplaces, as well as the other costs formed at the social level. Data published in [17] point out that in the period from 2013 to 2020, necessary investments for transmission and distribution networks and for flexible generation amounts 40-50% of the investments necessary for i-RES assets. However, this percentage amount is influenced and by considered i-RES structure, i.e. the ratio of PV and wind turbine capacities, the ratio of off-shore and on-shore wind turbine capacities, as well as the space distribution of the facilities. In [18] it is stated that investments for 42.100 km of new lines – without the off-shore grids and electricity highways is assessed on 100 billion euro. These lines are foreseen for transmission i-RES generated electricity from north areas (Baltic see) to the south industrial centers in Germany. Previous figure, according to our estimation, amounts 55% of the investments in i-RES made until 2016 in Germany expressed in 2016 euro. In [19] is quoted necessity of 3500 km of high voltage "high way" transmission lines, 140000 km of middle voltage lines and 240000 km of low voltage lines that have to be build up to 2030, while estimates of needed investments for Germany amount to €20 billion euro. Estimates for grid improvements within the scope of i-RES penetration made by EPRI and cited in [20] amount to $500 billion.

A more extensively developed transmission and distribution network contribute to a better i-RES's capacity credit.

It looks reasonable to be assumed, as bottom limit, the additional investments in electricity transmission and distribution networks as 50% of investments in i-RES. Assuming that the other part of the necessary system costs like the cost of closing the coalmines and related compensation for loss of workplaces also amount 50% of investments in i-RES, it can be accepted in the first approach $a_{ct} = 1{,}0 \cdot f_{ct}$. Similarly, for the numerical analysis presented in this paper, arbitrary is accepted $w_{ct} = 0{,}2$.

In Fig. 2 are presented calculated values of the $3E_{TT}$ Indicator as function of the fraction of hard coal and lignite fired technologies substituted by CO_2-free technologies. Two CO_2-free technologies are considered i.e., nuclear power plants and wind turbines. Nota bene, competitiveness of the power system is as better as is lower numerical value of $3E_{TT}$ Indicator. The results point out that $3E_{TT}$ Indicator is enough sensitive for the competitiveness analysis. The results also point out that technology transition from lignite fired and hard coal fired thermal power plants to nuclear power plants enable better power system's competitiveness than in the case of the transition to wind turbines.

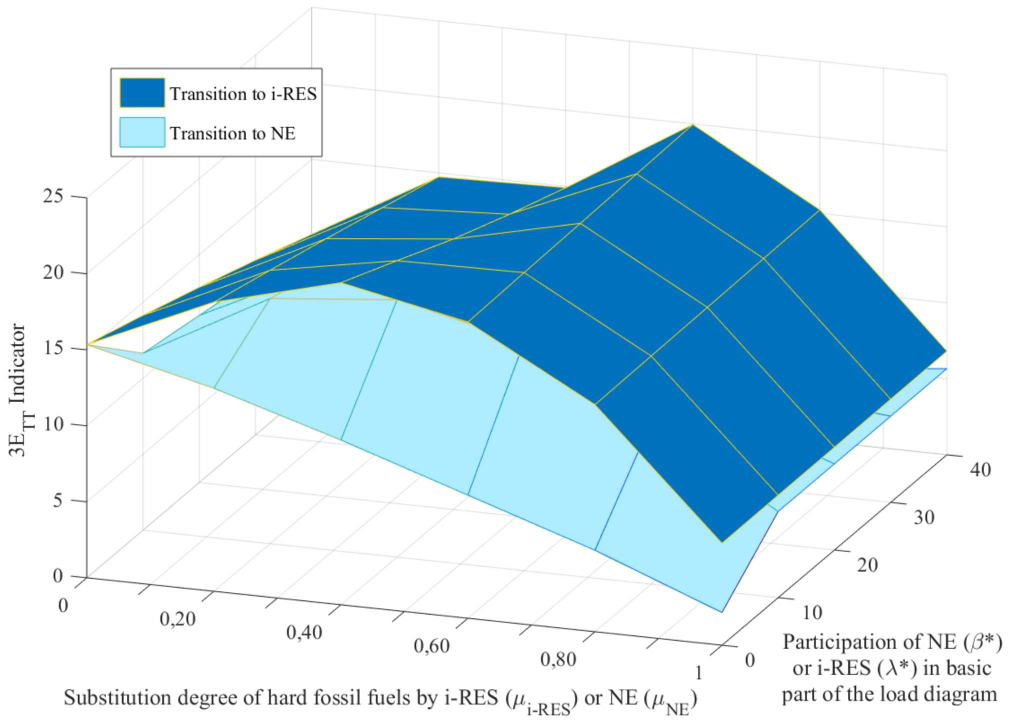

Fig. 2 Comparison of power system's competitiveness in technology transition using $3E_{TT}$ Indicator

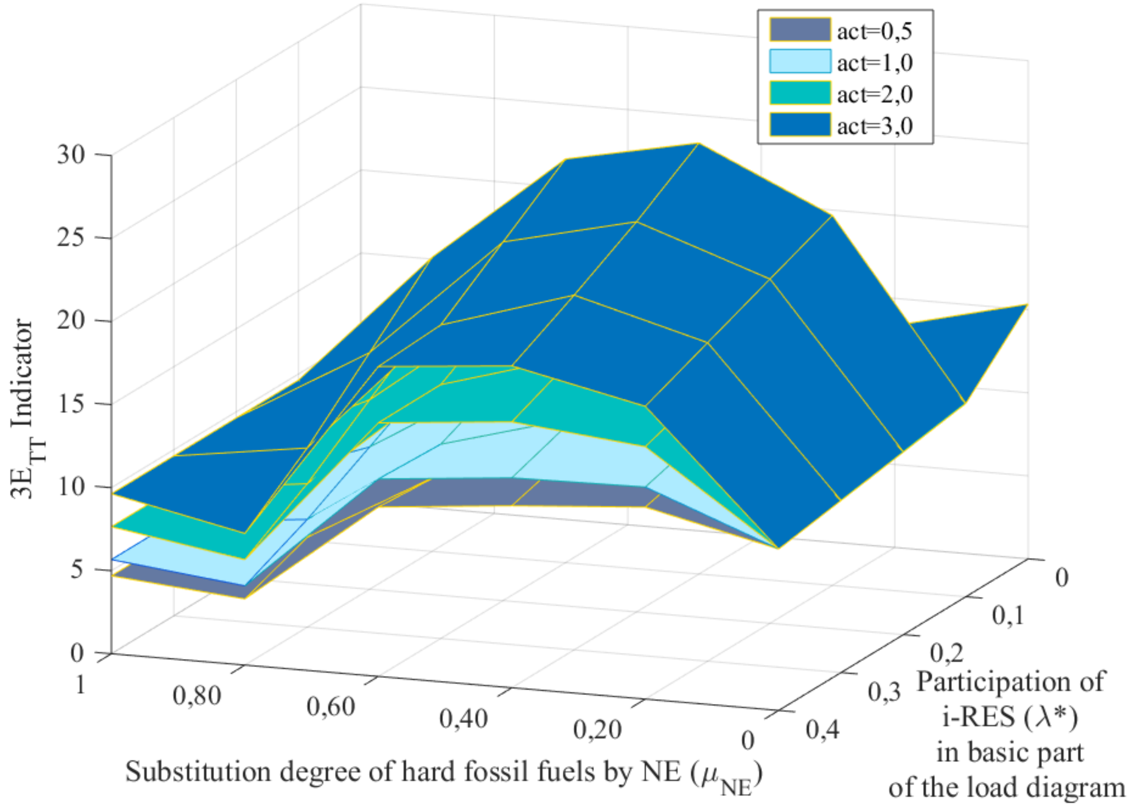

Fig. 3 Sensitivity of the $3E_{TT}$ Indicator for the system costs change (parameter a_{ct}) in the case of the substitution with NPPs

In Fig. 3 are presented calculation results of the 3E_{TT} Indicator's sensitivity to changes in system costs (parameter a_{ct}) for the case of the transition to nuclear power plants. As mentioned above, system costs comprise additional investments in electricity transmission and distribution networks, as well as other extra costs like the cost of closing the coalmines and related compensation for loss of workplaces, as well as the other costs formed at the social level. The results point out that doubled numerical value for the system costs ($a_{ct} = 2{,}0 \cdot f_{ct}$) causes increase in numerical value of the 3E_{TT} Indicator for about 20 to 33%, depending to the currant values of μ_{NE} and λ^*. In contrary halved numerical value for the system costs ($a_{ct} = 0{,}5 \cdot f_{ct}$) reduces numerical value of the 3E_{TT} Indicator for about 15 to 21%, depending to the currant values of μ_{NE} and λ^*. It has to be emphasized that above values of system costs (parameter a_{ct}) represents rather rough estimate. That is why the analysis is performed and with high value of $a_{ct} = 3 \cdot f_{ct}$ (see Fig. 3). However, in each case of the power system's technology transitions analysis a more detailed estimate of a_{ct} is highly recommended.

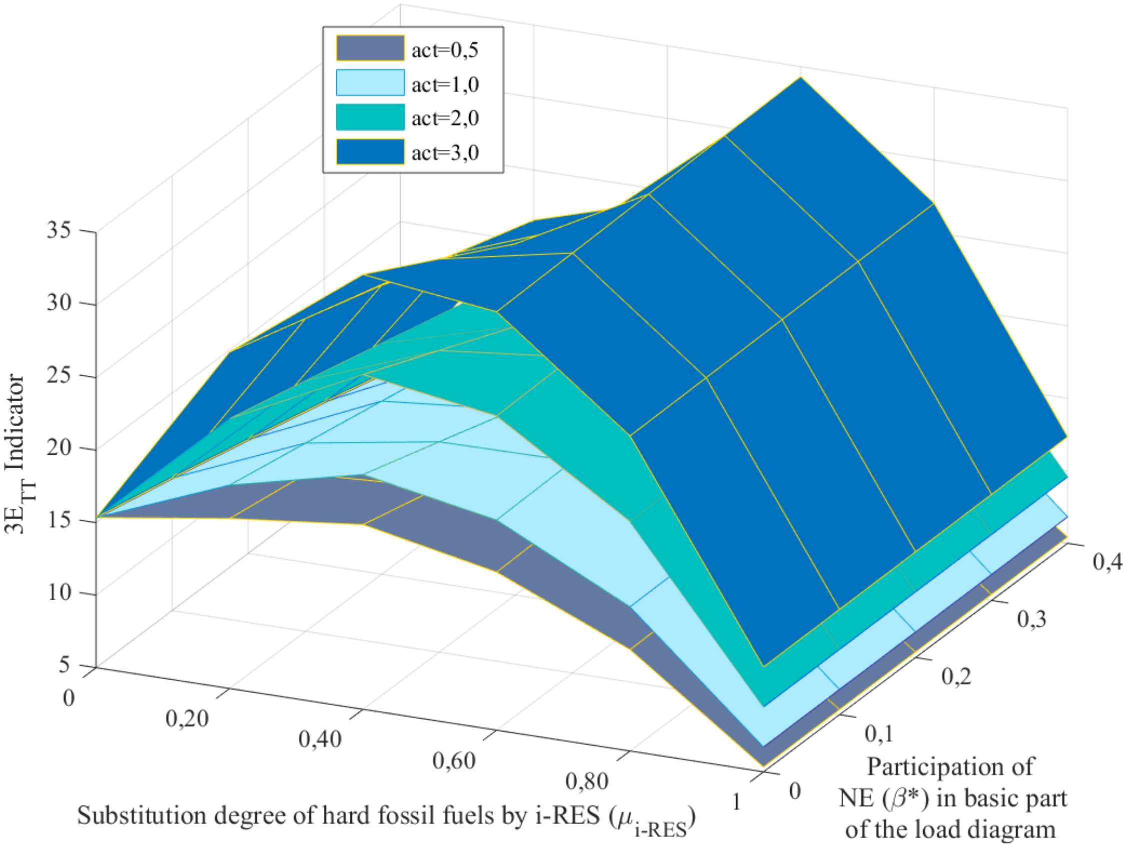

Fig. 4 Sensitivity of the 3E_{TT} Indicator for the system costs change (parameter a_{ct}) in the case of the substitution with i-RES

In Fig. 4 are presented calculation results of the 3E_{TT} Indicator's sensitivity to changes in system costs (parameter a_{ct}) for the case of the transition to wind turbines. The results point out that doubled numerical value for the system costs ($a_{ct} = 2{,}0 \cdot f_{ct}$) causes increase in numerical value of the 3E_{TT}

Indicator for about 30 to 40%, depending to the currant values of $\mu_{i\text{-}RES}$ and β^*. In contrary halved numerical value for the system costs ($a_{ct} = 0{,}5{\cdot}f_{ct}$) reduces numerical value of the $3E_{TT}$ Indicator for about 19 to 24%, depending to the currant values of $\mu_{i\text{-}RES}$ and β^*. It can be concluded that the technology transition from lignite and hard coal power plants to i-RES is more sensitive to changes of the numerical values of system costs.

Further is performed the sensitivity analysis to changes in the ratio of written-off assets cost and the annual amount of fix cost in equilibrium state w_{ct}, for both considered technology transition options, i.e. the transition to i-RES as well as the transition to nuclear power plants. Obtained results point small sensitivity in each of the considered transition options. For example, in the case of technology transition to nuclear power plants, the increase of 50% (from w_{ct}=0,2 to w_{ct}=0,3) causes decrease in numerical value of the $3E_{TT}$ Indicator for about 4 to 6%, depending to the currant values of μ_{NE} and λ^*. In contrary halved numerical value for the written-off assets cost (from w_{ct}=0,2 to w_{ct}=0,1) increases numerical value of the $3E_{TT}$ Indicator for about 4 to 6%. Similar relations are obtained and in the case of technology transition to i-RES. For example the increase of 50% (from w_{ct}=0,2 to w_{ct}=0,3) causes decrease in numerical value of the $3E_{TT}$ Indicator for about 3 to 6%, depending to the currant values of $\mu_{i\text{-}RES}$ and β^*. In the case of halved numerical value for the written-off assets cost (from w_{ct}=0,2 to w_{ct}=0,1) increases numerical value of the $3E_{TT}$ Indicator for about 2,5 to 5%, depending to the currant values of $\mu_{i\text{-}RES}$ and β^*.

Competitiveness of the power system's technology transition in the domain of existing technology portfolios is analyzed for selected nine European states. Eight of them are EU member states and one (Serbia) is not. Six states have nuclear power plants in operation (France, Germany, Hungary, Bulgaria, Belgium and Netherland), while the other three (Austria, Serbia and Greece) have not. For each considered state are assumed the same two hypothetical technology transition rotes, i.e. substitution of solid fossil fuels technologies with wind turbines only or with nuclear power plants only. Obtained results point out that in each state better power system's competitiveness can be achieved if nuclear power plants substitute lignite and hard coal fired power plants than if wind turbines are used for the substitution.

4.2 Dispatchability

An important feature of a power system in technology transition is its capability to change the power on demand. In references [21, 22] is introduced the technology portfolio's assured capacity (ACT) Indicator for indicating power system's capability to change the power on demand. In Fig. 5 are presented calculated values of ACT Indicators for the general case of power systems portfolio, the same as is considered in previous analysis and calculation of $3E_{TT}$ Indicators. In the case of the power system's technology transition to i-RES there is strong reduction of the systems capability to change the power on demand. This situation is somewhat improved with increase of nuclear power plants participation in residual load. On the other hand, technology transition to nuclear power plants enable increase of the power systems capability to change the power on demand. In this case, increase of i-RES in residual load domain causes some decrease of ACT indicator.

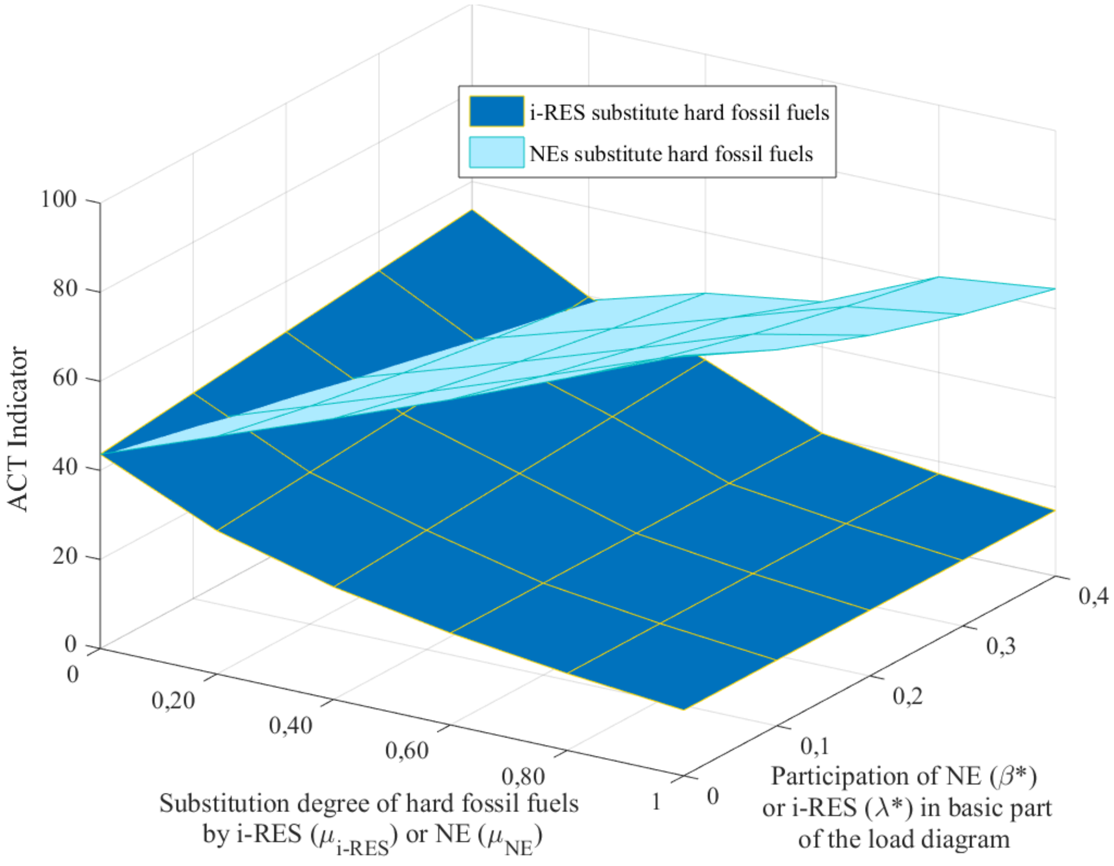

Fig. 5 Comparison of ACT Indicators for Substitution of hard fossil fuels by i-RES or NPPs

In Fig. 6 are presented calculated values of the dispatchability indicators (DI) for the general case of power systems portfolio, the same as is considered in previous analysis. The calculations are performed in accordance with the procedure given in [22]. From Fig. 6 it can be concluded that the dispatchability indicator shows trends very similar to those of ACT Indicator.

Numerical values of ACT and DI Indicators given in Figs. 5 and 6 correspond to the most conservative ones. In principle, there are three options for improving power systems capability to change the power on demand.

Together with investments in i-RES can be also made investments in the equipment for improving dispatchability of the system. For that, available technologies are pumped-hydro storage (PHS), compressed air electricity storage (CAES) facilities and batteries. On the other hand, including such equipment into technology portfolio condition higher amount of overall investments and therefore increase of $3E_{\text{TT}}$ Indicators numerical value, i.e. reduction of the system’s competitiveness in that respect. This problem is in detailed analyzed in reference [22], with PHSs as means of improvement power system's dispatchability.

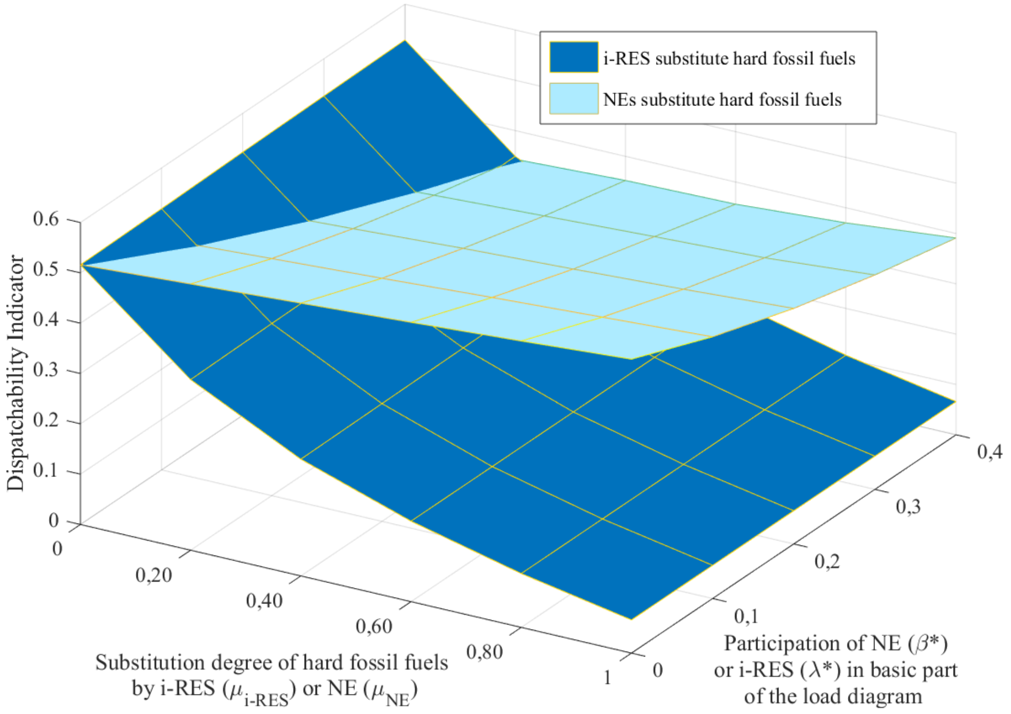

Fig. 6 Comparison of DI Indicator for Substitution of hard fossil fuels by i-RES or NPPs

The other option is in line with the study presented in [23], where it is concluded that to a wind penetration of 10%, corresponds the increase of necessary reserve capacities for about 2-10%. It implies, during a technology transition to keep some of the CO_2 dependable plants in the certain stage of readiness for operation in the cases where they can be successfully used in meeting the demand requirements. For example, in the case when weather conditions reduce electricity generation by i-RES with simultaneously increase of the consumption load. In Europe, such conditions can last ten to fifty hours in continuum [24] allowing inclusion some of the power plants that stand in specific sort of standby in meeting the power demand. However, in this option, there are many "ifs" and "whens" and that make very difficult a general approach. Therefore, in each case of a power system a specific screening procedure must be followed with the tasks to define possible periods of load changes and frequency of its occurring and after that from available power plants in standby to select those that can meet such load changes in available time. After passing through the screening procedure, it can be determined which power plants, with which effects and under which conditions can participate in meeting the load demand during the power systems technology transition.

Third option, as a part of overall technology transition, implies application of demand response controls of end use appliances in reduction of power picks [25].

5. CONCLUSIONS

There are ongoing discussions, mainly in some EU countries, about drastic changes in technology structure of the portfolios for electricity generation in sense of hard coal and lignite fired power plants phase out. This drastic change can be named as third technology transition of power systems. The third technology transition occurs in developed countries with rather small annual increase in electricity consumption, due to widely applied systems of measures for improving energy efficiency and energy saving. Target is further and significant reduction of CO_2 emission. There are many sever consequences of such a drastic change in power system's technology structure. Among them are necessity of greater investments in the assets, more expensive electricity, reduction of the power systems ability to change the power on demand, closing workplaces in certain parts of the industry like mines and others.

Competitiveness of a power system in technology transition regarding investments, CO_2 emissions and energy generated, is quantified with numerical value of $3E_{TT}$ Indicator. The general analysis, performed for the hypothetical power system comprising five electricity-generating technologies, points out that transition from solid fossil fuels technologies to nuclear power plants enable better competitiveness of the power system than in the case of the transition to wind turbines. Sensitivity analysis points out that the mostly influenced parameter on the power system's competitiveness in technology transition is the relative cost for other non-electricity generation purposes (a_{ct}).

Competitiveness analysis of the power systems in hypothetical technology transition for selected nine European states pint out that the transition towards substitution of lignite and hard coal fired power plants with nuclear power plants appears as better option compared to the transition towards substitution with wind turbines in each considered state.

Power system's technology transition, in principal can has important consequences on ability of the power system to change the power on demand as was analyzed in literature [13, 22]. Competitiveness of a power system in technology transition regarding dispatchability is quantified with numerical values of ATC and DI Indicators already defined in [21, 22]. Obtained results should be understood as the most conservative ones. For improving dispatchability of a power system in technology transition available options are application of energy storage technologies, holding some of substituted coal fired power plants as reserve ones, as well as application of demand side management technologies. Application of any or all of these technologies condition addition investments and certain increase of operation and maintenance costs, and in that respect corresponding reduction of power system's competitiveness with final result the increase of electricity price.

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