A CONTRIBUTION TO EVALUATION OF NUCLEAR POWER PLANTS COMPETITIVENESS USING 3E INDICATOR
One Possible Approach

by

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Original scientific paper
https://doi.org/10.2298/TSCI190404294G

The strong restrictions of greenhouse gasses emissions and the high penetration of intermittent renewable energy sources are the frame for researching more closely the contribution of nuclear power plants to competitiveness of corresponding technology portfolio for electricity generation. For the competitiveness indication 3E indicator is applied. The 3E indicator is expressed as the function of two variables that indicate the configuration of the technology portfolio i. e. participation of intermittent renewables in covering overall electricity load and participation of nuclear power plants in covering the residual electricity load. Obtained results point out that an increase of nuclear power plants participation in residual load contributes to the increase of the technology portfolio's competitiveness, i. e. to the reduction of the 3E indicator's numerical value. On the other hand, an increase of intermittent renewables participation in overall load in principle contributes to the decrease of the technology portfolio's competitiveness, i. e. to the increase of the 3E indicator's numerical value with the maximal value at the certain participation rate. The competitiveness of the technology portfolios for electricity generation in eleven European countries is also examined. The results point out that the country with highest participation of intermittent renewables in overall load domain has the less favorable competitiveness, and the lowest annual equivalent operation time of the technology portfolio. On the other hand, the country with highest participation of nuclear power plants in residual load domain has the most favorable value of 3E indicator and the highest annual equivalent operation time of its technology portfolio.

Key words: *nuclear power plants, competitiveness, 3E indicator*

Introduction

General understanding of notation competitiveness is related to the ability to compete successfully. The concept of competitiveness was evolving during the time, as it was explained in [1]. Modern understanding of this notation is closely-knit to Michael Porter and his definition of competitiveness. After Porter notation the competitiveness was widely used, often contributed to different entities, like company, industry even person. Serious controversies were created with attributing the competitiveness to countries. Many recognized scientists were strongly against such approach [1]. Competitiveness can be considered only qualitatively or both qualitatively and quantitatively. In the second case some metric is necessary. Porter in his work has

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defined four broad attributes as the most influenced factors and called them diamond of competitiveness. These broad attributes are: firm strategy, structure and rivalry; related and supported industries; demand conditions; and factor conditions. More specific object of competitiveness like process industry or energy technology, conditions more specific and more precise metric for quantitative assessment of the competitiveness. On the other hand qualitative consideration of the competitiveness needs adequately wide approach. An example of qualitative approach to the general understanding of competitiveness in the field of energy, environment, natural resources and business is presented in [2].

In this paper we shall attribute the competitiveness to the electricity generating technologies, as well as to the complex of energy technologies that as technology portfolio operate together within the same system. The degree to what considered technology portfolio satisfies certain condition is assumed as the measure for the competitiveness. In principle there are many different conditions that all together determine the level of the competitiveness. The most important are energy conditions, economy conditions, environment conditions and technology conditions. Our assumption is that a technology portfolio can better compete to the others if it satisfies selected conditions to the higher degree than the others portfolios.

On the other hand, the competitiveness of a certain electricity generating technology may be fairly determined in accordance to its contribution to the competitiveness of corresponding technology portfolio. So the technology portfolio is the domain where competitiveness of the certain electricity generating technology has to be measurable and useful determined.

This research in the direction of the competitiveness of electricity generating technologies, as well as the technology portfolios came as the continuation of the previously performed research whose results were published in [3-5].

In November 2016 came into force the United Nations Framework Convention on Climate Change, known as Paris agreement, previously adopted in December 2015. The Paris agreement set as a target significant reduction of anthropogenic GHG emissions, and thus limiting the increase of the global average temperature to less than 2 °C compared to the pre-industrial level. So. it can be assumed that the reduction of CO_2 emissions from energy plants, industry and traffic and thus unloading the environment of CO_2 content, nowadays become the social and political request of the highest order to which the design and operation of power plants and overall energy systems must be dedicated. First and the most promising approach is to build the plants that generate electricity with no CO_2 emissions. Fulfillment of this request of the higher order contributes to the better competitiveness of the considered technology and/or technology mix. Or, in the other words, how far reaches the considered technology and/or the technology portfolio in fulfillment this request of the higher order can be considered as one of the dimensions of its competitiveness.

Nuclear power plants today

Nuclear power plants (NPP) allow generation of dispatchable electricity with no CO_2 emission and this is their great advantage compared to the other thermal power plants, and this is one of the reasons why the interest for NPP is not only maintained until nowadays, but also and appreciably increased in the last two decades. This can be recognized not only by viewing scientific articles published in the literature, but also and by overview of new build plants. At the end of 2016 there were 447 operational nuclear reactors with total installed capacity of 392 GWe in altogether 30 countries in the world, as it is reported in [6] and these capacities generated 2476 TWh of electricity in the same year [6]. Average capacity factor of the NPP in

2016 in the world was 80.7 (7052 hours at full load), but 33% of all reactors in the world had average capacity factor of 90% that correspond to 7880 hours at full load [7].

Simultaneously, 60 new reactors are under construction in altogether 15 countries [6]. Out of this number 20 reactors are under construction in China and 15 in Russian Federation, India and Pakistan [7]. Russia also builds NPP in Belarus, China, Hungary, India, Iran and Turkey, and is involved in Algeria, Bangladesh, Bolivia, Indonesia, Jordan, Kazakhstan, Nigeria, South Africa, and Tajikistan [7]. According to the Chinese government's Energy Development Strategy Action Plan, it is foreseen in the period 2014-2020, all together 58 GW new nuclear capacities to be built until 2020 and in addition for another 30 to start construction [7].

In normal operation with low-strain operating mode NPP can realize gradient load changes of about 5%/min of the nominal unit's power [8]. In principle such gradients enable NPP to operate in load following mode. Considering unit's nominal powers of existing thermal power plants, above figure of 5% per minute correspond to gradient load change of about 65 MW/min which is over 50% greater than gas fired CCGT and about twice as those of coal fired power plants [9].

The NPP can also achieve very low levels of loads. The results of the study conducted in 2009 in Germany, which were published in [8] state the minimum loads that can achieve certain NPP designs (like *Vor-Konvoi* and *Konvoi*) amounts only 20% of the nominal power. Such flexibilities are highly appreciated by the designers and operators of the modern electric energy systems.

The NPP have generally sufficient safety margins that even remain if the impact of an event exceeds design limits [10]. This fact is the basis in the approach toward refurbishment and life extension of the existing NPP. According to [11] the refurbishment of the plant turbine generator combined with utilizing the benefits of initial margins in reactor designs, digital instrumentation and control technologies and investments in other enhanced generating capacity can increase plant output by up to 15-20%. In USA for 81 out of 100 units have already been accepted life extension for a 20 year period and operating licenses were issued for operation until 60 years lifetime, while the others are in the process of applying [11]. Also, as is reported in [11], the nuclear regulation commission is preparing to consider license extensions up to 80 years lifetime. Canadian government has already signed the contracts for the refurbishment and life extension of six reactors at the Bruce generating station [7]. However, not all reactors can be upgraded and refurbished for long-term operation generally due to economic reasons. But it is of high importance the existence of proven economical acceptability for upgrading, refurbishment and life extension.

Looking forward, the new NPP will have better safety, better operating flexibility and better economy. Safety as extremely important condition for developing and designing of NPP is further increased by introducing passive safety systems in so called Generation III+ [12]. Besides, the economy of NPP will be improved, among others and by allowing higher burnups [13].

Further, price of electricity generated in NPP is very competitive to the prices from other thermal energy plants, regardless to high investments needed for NPP [13, 14].

There are different taxation policies toward NPP in different countries. So, in Sweden, Belgium and Germany the taxes for nuclear energy in 2014 were 6.7 €/MWh, 5 €/MWh, and 7.3 €/MWh, respectively, [13]. On the other hand, according to [13], USA is the only country which has offered any subsidy to nuclear power production, with the tax credit of 19 $/MWh.

Public acceptance represents an important barrier toward wider use of NPP. Obstacles to increasing public acceptance are the subject of many performed analysis. In [15] are identified four main ones as: the safety issue, the radioactive waste management, the security and the problem of trust. All this issues can be solved at the social and environmental acceptable levels. Also, it can be quoted that annual production of radioactive waste of all NPP in the world nowadays amounts 7000 tonne per year [6]. This figure is disproportionate small when compared to total annual amount of industrial waste, including high toxic one, which is for the whole world estimated on 200 million tons per year [2]. Regarding the obstacles, effective new safety paradigm has to be developed and publically presented in order to encourage motion in positive direction, as it is underlined in [7].

Technology portfolios

In an electric energy system with intermittent RES (i-RES) the overall annual energy consumption demand is distributed on certain electricity generating plants in the two ways. The RES with variable load (photovoltaic and wind generators) have the priority in electricity in-feed, and therefore they produce as much electricity as they can. The electricity generated by i-RES is subtracted from the total energy needed which is defined by the annual load duration curve of the referent system, as can be seen in fig. 1. The remaining residual load, which is characterized with corresponding residual load duration curve, is distributed on the power plants in the system in accordance to the merit order principle. The greater percentage of annual RES in-feeds results in lower residual load available for coverage by dispatchable plants like thermal power plants (conventional fossil fueled and NPP) and hydro power plants.

In the case of very big amount of electricity produced by variable RES, residual load can become even negative, fig. 1. Negative residual load means that there is surplus of electricity generated by i-RES even if all dispatchable sources *i. e.* thermal power plants are switched off.

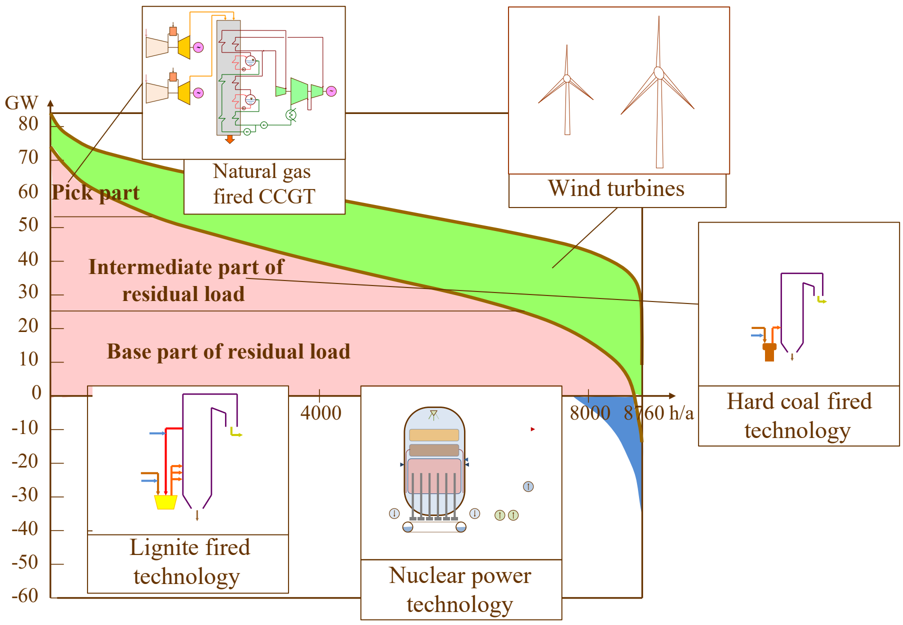

Figure 1. Graphical presentation of technology portfolios used as referent for simulation research

Conditions established by high percentage of i-RES in-feed in the electric energy system become much more sever for operation of dispatchable plants compared to the conditions without or with small generation of i-RES electricity.

Smaller residual load means smaller needs for electricity generated by dispatchable plants *i. e.* smaller market for these plants with the end effect manifested in their smaller annual electricity generation. As a consequence fix costs per unit of electricity generated become greater, or alternatively, if the selling price of the electricity remains unchanged the plants income become considerably smaller. In both cases there is significant economic impact.

Variable (intermittent) character of photovoltaic and wind electricity generation requires fast load changes of the plants operating in residual load domain. In addition, these plants more frequently have to change load, as well as to shut down and start up, than it is case in the systems with smaller participation of i-RES. The interval of load increase/decrease is also great, resulting in smaller value of the plants average annual load. Further, the plants are pressed to operate at low loads that are significant lower than earlier so called minimal loads of the thermal power plants.

The referent technology mix that was considered in simulation research consists of wind turbine farms as i-RES. For the base part of the residual load are assumed lignite fired power plants and NPP, for intermediate part are assumed hard coal fired power plants, while for the pick part of the residual load are assumed natural gas fired combined cycle gas turbines (CCGT), as presented schematically in fig. 1. In addition, lignite fired power plants and hard coal fired power plants are considered in four variants, *i. e.* as existing technology, as existing technology combined with carbon capture and storage (CCS) technology, as advanced technology (with higher efficiency) and as advanced technology combined with CCS technology. Natural gas fired CCGT are considered as existing technology and as the existing technology combined with CCS technology. Development of CCS technologies has moved far away and the achievements in this development are discussed in [16, 17]. The considered technology mixes are somewhat simplified compared to the general case of a complex technology structure. The simplifications are aimed to enable as clear as possible presentation of the influenced variables on the final result without harming its exactness and generality.

Competitiveness of technology portfolios and the indicators

The configuration of referent technology portfolio with i-RES is indicated by the participation of CO_2 free, non-dispatchable technologies like wind turbines in total load domain λ [kWh/kWh_{tot}], and by the participation of nuclear power plants in the basic part of the residual load domain β [kWh/kWh_{res}]. The higher value of indicator λ conditions greater part of the prioritized electricity in-feed on the expense of appropriate reduction of residual load domain. The higher value of indicator β indicate greater participation of NPP on the expense of appropriate reduction of lignite fired thermal power plants in basic part of the residual load domain [18].

There are a number of indicators used in modern power engineering practice to indicate efficiency, performance, environment impact and competitiveness of electricity generating technologies. Some of them were listed and analyzed in [19]. For indicating competitiveness of technology portfolios as the complex technology structures with i-RES we selected to used 3E indicator, as well as the capacity utilization (CU) indicator.

As explained in [20, 21] the 3E indicator is expressed in analytically form by the equation:

$$3E = \frac{\sum_{i=1}^{n} f_{cESi} \cdot \sum_{i=1}^{n} m_{CO_2 ESi}}{\sum_{i=1}^{n} e_{ESi}} \tag{1}$$

where expression f_{cESi} denotes annual amount of fix cost (expressed in millions euro per year) for i[th] electricity source, m_{CO2ESi} – denotes annual amount of CO_2 emission (in thousand tons per year) of i[th] electricity source, e_{ESi} – the electricity generation (in MWh per year) of i[th] source, while n – denotes the number of electricity sources comprising all steam turbine generators, gas turbine generators, wind turbine generators, hydro turbine generators and solar electricity sources.

The competitiveness of the considered portfolio for electricity generation is as better as is lower value of 3E indicator. The condition for improving the portfolio with new designs and/or new technologies is resulting decrease of the value of 3E indicator.

As an additional indicator is used CU indicator. For a considered year it expresses the time, in hours per year, necessary that all installed capacities, if running at their nominal loads generate the same quantity of electricity as in actual real load conditions. This indicator is analogues to the equivalent number of operation hours at full load for the power plant, since it explains the same, but for the whole system. In analytical form this indicator is defined by following equation:

$$CU = \frac{\sum_{i=1}^{n} e_{ESi}}{\sum_{i=1}^{n} P_i} \tag{2}$$

The analysis and the results

The analyses are performed using analytical model described in [5] with necessary adoptions for the case. A more or less typical central European electric energy system is selected as the referent one and the load duration curves from fig. 1 are assumed as valid. The analyses were performed numerically with the indicators λ and β that indicate the configuration of the considered technology portfolios as independent variables. Net efficiencies of the technologies that were used in the analysis are presented in tab. 1. Costs of the assets correspond to prices in 2016, according to [22, 23], and are presented in tab. 2.

The average values of CO_2 generation per unit of fuel energy for different fuels are calculated using data from reference [24].

In fig. 2 are presented calculated values of 3E indicator for four basic technology portfolios for electricity generation. The difference among these basic portfolios is in the technology selected for the intermittent part of the residual load. In the base part of the residual load are considered lignite fired power plants existing technology and NPP in each of the

Table 1. Net efficiencies of the considered technologies [%]

Technology	LfPP	HCfPP	CCGT	NPP
Existing	42	43		
Existing + CCS	33	34		
Advanced	44	50	60	33
Advanced + CCS	35	41	53	

Table 2. Costs of the considered technologies [€ kW^{-1}]

Technology	LfPP	HCfPP	CCGT	NPP
Existing	3515	3056		
Existing + CCS	4920	4280		
Advanced	4045	4584	963	5206
Advanced + CCS	5450	5806	1830	

four basic portfolios. From the fig. 2 it follows that an increased share of electricity generated by NPP in the base part of the residual load domain, starting from zero value ($\beta = 0$), enables decrease of 3E indicator, and thus improvement the portfolios competitiveness. On the other hand, increased share of electricity generated by i-RES in total load domain starting from its zero value ($\lambda = 0$) causes the increase of 3E indicator, and thus reduction of the portfolios competitiveness. Also, there exists a value of λ_{3Emax} for which 3E indicator reaches its maximum, *i. e.* the competitiveness the minimum. For further increase of λ above value λ_{3Emax}, the value of 3E indicator decreases, and in some cases (not presented in fig. 2) can even fall under its starting value for $\lambda = 0$. In the case of the basic portfolios presented in fig. 2, maximal values of the 3E indicator are obtained at $\lambda = 40\%$.

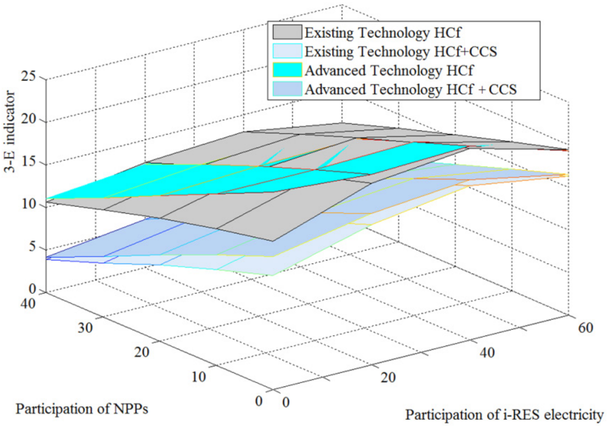

Figure 2. Graphical presentation of 3E indicator in the case of existing lignite fired technology in the base part of the residual load (*for color image see journal web site*)

In all four basic technology portfolios from fig. 2 the best values of the 3E indicator are obtained with 40% of NPP in residual load domain and 0% of variable i-RES in overall load domain. In that respect the exception is the case with advanced hard coal fired technology. However, this basic portfolio together with the basic portfolio with existing hard coal fired technology have much lower competitiveness than the other two considered basic portfolios. The existing hard coal fired technology combined with CCS enables better portfolios competitiveness in the case of the relatively small participation of i-RES, than the advanced hard coal fired technology also combined with CCS. In contrary, for the bigger values of the parameters λ and β, the portfolio with advanced hard coal fired technology combined with CCS enables better portfolio competitiveness.

Passing over from existing lignite fired technology to existing lignite fired technology combined with CCS technology in the base part of the residual load domain enables significant improvement of the corresponding portfolios competitiveness, as can be recognised in fig. 3. In this case we can notice that the maximum value of the 3E indicator occurs at $\lambda = 20\%$, what is significantly lower than in the previous case in fig. 2.

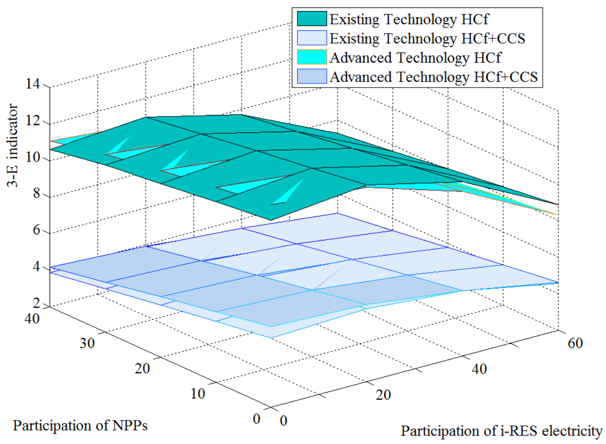

Figure 3. Graphical presentation of 3E indicator in the case of existing lignite fired technology combined with CCS in the base part of the residual load (*for color image see journal web site*)

The same model is applied for calculation values of 3E indicator for the selected group of eleven European countries. Eight of them have NPP in operation while the rest 3 have not. Participation of NPP in residual load in these eight countries *i. e.* Germany, France, Hungary, Bulgaria, Belgium, Netherlands, Slovakia, and Finland roughly amounts: 20%, 82%, 54%, 34%, 44%, 4%, 24%, and 17%, respectively. In fig. 4 are presented obtained values of 3E indicator as function of selected variables λ, and β, for the selected group of eleven European countries. All assets are assumed as new one, *i. e.* no repayments of the investments are considered since there was lack of available data. In the case that partially write-off of the asset is included in assessment of 3E indicator, its numerical value will be lower. Data on electricity generating capacities, as well as the generated electricity in considered countries are taken from references [25-27]. The data are valid for the year 2015. For the purpose of this analysis in the data for the biomass are considered those related to investments and electricity generated, but not related to CO_2 emissions. The distribution of 3E indicator in principal corresponds to those from fig. 2. However, there are meaningful differences in the numerical values of 3E indicator among considered countries as can be seen in fig. 4.

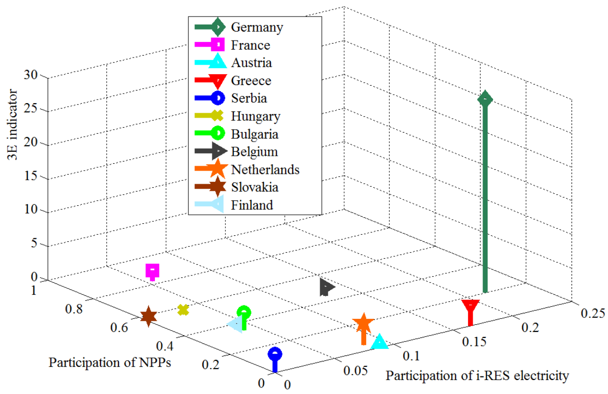

Figure 4. Graphical presentation of estimated values of 3E indicator for selected group of eleven European countries (*for color image see journal web site*)

Much bigger value of 3E indicator for Germany looks as a consequence of the certain *Overinvestment* in the assets for electricity generation that operate producing energy small number of hours per year. Calculated values of the CU indicator for each European country from the selected group, point out that Germany has the lowest value of slightly fewer than 3000 h/y in nominal capacity, while France has about 50% greater value that amounts 4460 h/y. In European conditions, according to [28], NPP have the highest value of CU of over 7500 h/y; while photovoltaic plants have the lowest value of about 1000h/y. Wind generators have value of CU in principle in the range from 2000 h/y (on-shore) up to 3500 h/y (off-shore). However, these figures for i-RES were not reached in 2015 in the considered countries.

Other components of NPP competitiveness

Many studies were conducted by different organizations in order to estimate the life cycle GHG emissions of NPP. The studies comprise NPP life cycle as well as the corresponding fuel cycle life cycle. The results of the studies are analyzed and compared in reference [29]. The results vary among them mainly due to arbitrary selection of system boundaries or due to the fact that some processes in nuclear fuel cycle were omitted. In the World Nuclear Agency study on lifecycle GHG emissions for various electricity generating technologies [30] are comprised results of over 20 published studies. The results are arranged in three columns: lower range, upper range, and mean. The figures from the column *Mean* (assuming them as the most realistic ones) point out that nuclear power plants belong to the group of three technologies with the smallest lifecycle GHG emissions, and with about 12% greater value than the two the smallest ones – hydro power plants and wind generators.

Finally, we can mention the comparative research of Hundt *at al.* [8] in two scenarios for NPP in Germany. First scenario is NPP phase out in 2023 and second one is lifetime extension after 2023. The results point out that in 2030 in the second scenario (lifetime extension) yearly operating costs will be lower, average wholesale price of electricity will be lower and CO_2 emissions will be lower in comparison to the phase out scenario [8]. In addition it was found that neither of the two scenarios is clearly superior with respect to the flexibility of the conventional thermal generating mix [8].

Conclusions

In the paper is considered present status of NPP regarding the number of units in operation and in construction, regarding their operation in the electricity generating systems with high penetration of i-RES, regarding refurbishment and life cycle extension, and regarding taxation and subsidy policies for them in different countries.

Competitiveness of NPP is analyzed. The research method is based on the concept to analyze the contribution of NPP to the portfolios competitiveness within which it operate. The competitiveness is defined as ability of the portfolio to compete to the others. As competitiveness indicator is selected 3E indicator previously developed and published in the literature [18-21]. The 3E indicator comprises annual amount of fixed costs, annual amount of CO_2 emitted and annual amount of electricity generated by the referent portfolio. As additional indicator is used equivalent operation time.

The results of theoretical model exploration are obtained for the simplified portfolio that comprise wind generators as i-RES, and in the base part of the residual load lignite fired power plants and NPP, in intermediate part hard coal fired thermal power plants, while in the pick part of the residual load CCGT. Lignite fired power plants and hard coal fired power plants were considered in four variants *i. e.* as existing technology, existing technology with CCS technology, as advanced technology, and as advanced technology combined with CCS. The results point out that with increasing participation of NPP in the referent technology portfolio, the competitiveness of the portfolio becomes better. With increasing participation of i-RES, the competitiveness of the portfolio becomes gradually less favorable, and after reaching a certain minimal value, it rises again.

The same model is applied for comparison of competitiveness of the complex technology structures in a group of nine European countries. Eight of them (Germany, France, Hungary, Bulgaria, Belgium, Netherlands, Slovakia, and Finland) have NPP in operation, while the rest three (Austria, Serbia, and Greece) have not. Obtained results point out that Germany as the country with highest participation of i-RES in electricity generation has much greater value of 3E indicator than France the country with highest participation of NPP in residual load domain. More detailed exploration pointed out that Germany has about 16% higher annual amount of fixed costs than France, but also and about 15 times bigger annual amount of CO_2 emissions than France [18]. The data are valid for the electricity generation in corresponding installed capacities in 2015, calculated with asset prices from 2016. Finally, we can mention that there are and other approaches to realize comprehensive balance and coordinated development among energy, economy and environment, like those explained in [31]. The target was to achieve the lowest cost on carbon emission reduction technology and to make adequate portfolio optimization. Existence of the certain limitations in the methods that are currently in use for generating performance indicators is recognized in [32].

All at all it can be concluded that law values of 3E indicator for the complex technology structures with high participation of nuclear energy in residual load reflects the significant competitiveness advantage of NPP. Published data on other components of nuclear power plant's competitiveness like life cycle emission of GHG sets NPP on the third place among the best ones immediately after hydro power plants and wind generators.

Nomenclature

e_{ESi} – electricity generation [MWh per year] of i^{th} source
f_{cESi} – annual amount of fix cost (expressed in millions euro per year) for i^{th} electricity source
m_{CO2ESi} – annual amount of CO_2 emission (in thousand tons per year) of i^{th} electricity source
P_i – nominal load

Greek symbols

β – participation of nuclear power plants in the residual load domain, [kWh/kWh$_{res}$]
λ – participation of CO_2 free, non-dispatchable technologies (like wind turbines and photovoltaic) in total load domain, [kWh/kWh$_{tot}$]

Acronyms

CCGT – combined cycle gas turbines
CCS – carbon capture and storage
CU – capacity utilization indicator
HCfPP – hard coal fired power plant
i-RES – intermittent electricity sources
LfPP – lignite fired power plant

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Paper submitted: April 4, 2019
Paper revised: June 9, 2019
Paper accepted: June 11, 2019