Ecology, Economy and Energy Evaluation of Electricity Generating Technologies Using 3E Indicator

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Abstract: The paper presents the results of technology option research on the paths towards the carbon free electricity generation. To that end three different technology mixes are considered. Each mix comprises i-RES and nuclear thermal power plants technologies, plus a combination of existing and advanced hard coal and lignite fired technologies with and without CCS. In order to enable quantitative measurements of the considered technology mixes, 3E Indicator is introduced. The principal application of the Indicator is described by appropriate model calculations for the general European conditions. The results show that the introduced 3E Indicator is suitable for analysis of the technological combinations for electricity generation within considered country. The analysis is exemplified by the estimation of 3E indicator for the installed capacities and electricity generated in the group of five European countries. The results show that the country with the highest participation of NPPs and/or HPPs and low participation of i-RES in electricity generation has the best i. e. the lowest value of 3E Indicator. On the other hand the country with the highest participation of i-RES and low to moderate participation of NPPs and/or HPPs has the conceivably highest value of 3E Indicator.

1 INTRODUCTION

Reduction of CO_2 emissions from energy plants, industry and traffic and thus unloading the environment of CO_2 content, nowadays become the social 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 plants that generate electricity with no CO_2 emissions or at least with the smallest possible emissions. As the response on the request tens thousands of renewable energy sources (RES) like photovoltaic and wind electricity sources were built in the world. However these sources can operate only when the weather allows it, and thus they belong to the intermittent ones.

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

In the case of very great amount of electricity produced by i-RES, residual load can become even negative (indicated by blue surface in Figure 1). Negative residual load means that there is surplus of electricity generated by i-RES even if all despatchable sources i.e. thermal power plants are switched off.

Conditions established by high percentage of i-RES in-feed in the electric energy system become much more sever for operation of despatchable

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plants compared to the conditions without or with small generation of i-RES electricity.

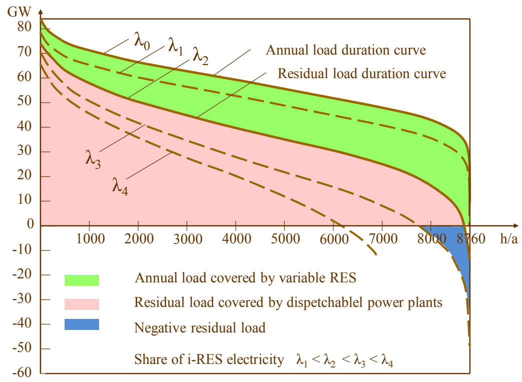

Figure 1: Annual load and residual load duration curves, according (Steffen and Weber, 2013; Wissel et al., 2008).

Smaller residual lad means smaller needs for electricity generated by despatchable plants i.e. smaller market for these plants with end effect manifested in their smaller annual electricity generation. As a consequence fixed 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 conditions great speed of load change of the plants operating in residual load domain. According to a rough estimate for the European occasions, the speed of power change from 20 MW / min to 70 MW / min, on average for several tens of hours, can be expected in due time. Beside great speeds of load changes, 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. All these issues condition faster ageing of thermal power plants, compared to the situation with small i-RES in-feeds.

Intermittent RES energy technologies used in the modern electricity generating systems are: wind generators – on shore (smaller air velocities) and off-shore (greater air velocities), and photovoltaic generators – on roof and on the soil.

The bulk of the residual load is mostly covered by thermal energy plants technologies as follows:

- Coal (hard coal or lignite) fired power plants based on existing or advanced technology (CFPP).
- Nuclear power plants (NPPs).
- Natural gas fired open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT).

Out of these three technologies, only nuclear power plants operate without any CO_2 emission, while others operate with certain CO_2 emissions. There are two technology options for emission reduction of fossil fuelled power plants. First is improving thermodynamic cycle efficiency. In the case of steam plants advanced steam conditions level of 37.5MPa/700^{0}C/720^{0}C can enable the increase of plants efficiency of 3 percent points in the case of lignite combustion and 4 to 6 % percent points with hard coal combustion (Fürsch et al., 2012). In the case of OCGT efficiency of about 40% and in the case of CCGT efficiency of about 60% can be obtained, while the turbine inlet temperatures TIT of the level of about 1500^{0}C is achievable (Bareiß et al., 2010). Second option is combining carbon capture and storage (CCS) technologies with either existing or advanced fossil fuelled thermal power plants. Development of CCS technologies has moved far away (Fouquet and Nysten, 2012; Kosel and Und, 2010). Advanced steam turbine/boiler technologies, as well as the CCS technologies are expected to be commercially available after 2020.

For utilizing electricity surplus in the domain of negative residual load corresponding capacities of pump storage hydro power plants (PSHPP), and/or compressed air storage (CAS) power plants and/or appropriate batteries are needed. However, the cost of electricity produced by these plants is high due to additional investments needed, as well due to unavoidable losses in the processes of energy conversion.

2 3E INDICATOR

Key process indicators are necessary for assessing environmental goodness and process effectiveness of industry's operation or business performance, as well as of the design of the technology system. In the field of energy and CO_2 emissions are in use: Carbon intensity, the KAYA identity and IPAT indicator. Carbon intensity is defined as the emission rate of a carbon relative to the energy imputed in the process (https://definedterm.com) and can be applied at the technology level, as well as on the companies or countries level. The other two are designed to assess general patterns of the relations among population, energy intensity, GDP and carbon intensity (KAYA) (http://www.tsp-data-portal.org/TOP-20-Generation#tspQvChart), as well as population, affluence and technology (IPAT) (https://en.wikipedia.org/wiki/Kaya_identity) at the state level. These factors are not enough sensitive on the changes in the design of electro energy systems and selection of different technology mixes that is aimed to satisfy the needs in energy produced and carbon intensity with as low as possible investments. Owners and designers of electricity generating systems need to have the indicator that will help in decision making for the new improvement of the system's patterns, as well as the related investments.

In designing an electric energy system the main targets are assumed to be: CO_2 emission as low as possible, electricity generation enough high to satisfy the needs and investments in the system as low as possible. Numerical values of the targets can be combined into one indicator, 3E indicator, which can be expressed in mathematical form by the equation:

$$3E = \frac{\sum_{i=1}^{n} f_{cESi} \cdot \sum_{i=1}^{n} m_{CO2ESi}}{\sum_{i=1}^{n} e_{ESi}} \tag{1}$$

In above equation f_{cESi} denotes annual amount of fixed 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} 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 PV and other solar electricity sources. By introducing obvious changes we obtain following equation:

$$3E = \frac{F_c \cdot M_{CO2}}{E} \tag{2}$$

Where F_c denotes total annual amount of fixed cost (expressed in millions euro per year) of all electricity sources, M_{CO2} denotes total annual amount of CO_2 emission (in thousand tons per year) of all electricity sources and E denotes total electricity generation (in MWh per year) of all electric sources. The electricity generating system is as better as is lower value of 3E indicator. The condition for improving the electricity generating system with new designs and/or new technologies is resulting decrease of the value of 3E indicator. In mathematical form it can be expressed as:

$$\Delta(3E) \langle 0 \tag{3}$$

Above inequality can be developed as:

$$\frac{\Delta F_c}{F_c} + \frac{\Delta M_{CO2}}{M_{CO2}} \langle \frac{\Delta E}{E} \tag{4}$$

Above inequality can be analysed for two cases. First is when investments are going to be spent only for reduction of CO_2 emissions. In that case the increase of electricity generation equals zero, so we obtain the condition in the form:

$$\frac{\Delta F_c}{F_c} \langle -\frac{\Delta M_{CO2}}{M_{CO2}} \tag{5}$$

This means that relative increase in investments must be smaller than relative decrease in CO_2 emission.

Second case is the general case where the investments are spent on increase of electricity generation and on decrease of CO_2 emission.

$$\frac{\Delta F_c}{F} \langle \frac{\Delta E}{E} - \frac{\Delta M_{CO2}}{M_{CO2}} \tag{6}$$

The relative increase in investments must be smaller than the difference of relative increase of electricity generation and relative decrease in CO_2 emission.

Advantage of the 3E indicator as defined by the equation (1) is its adequacy in comprising main influenced values, as well as its simplicity.

3 APPLICATION OF 3E INDICATOR

Above explained 3E indicator is used to analyse possible technology paths toward carbon free electricity production at the state level. For that, three cases of different technology mixes are selected. Each case is simplified and reduced on two technologies in base part of residual load; one technology in intermediate part and one in pick part of the residual load, as mentioned below.

Existing technology, lignite fired power plants and NPPs for basic part of the residual load, hard coal fired power plants for intermediate part of the residual load and gas fired CCGT power plants for the pick part of the residual load. No CCS technology is foreseen.

Existing technology lignite fired power plants and NPPs for basic part of the residual load, advanced technology hard coal fired power plants for intermediate part of the residual load and gas fired CCGT power plants for the pick part of the residual load. No CCS technology is foreseen.

Existing technology lignite fired power plants and NPPs for basic part of the residual load, advanced technology hard coal fired power plants with CCS technology for intermediate part of the residual load and gas fired CCGT power plant for the pick part of the residual load.

For the parametric analysis are selected following independent variables: the participation of i-RES in total amount of electricity generation expressed by indicator λ (kWh/kWh_{tot}) and the participation of NPPs in residual load expressed by indicator α (kWh/kWh_{res}). The analysis is performed numerically. The simplifications in defining technology mixes are introduced in order to present the approach clearer without harming its exactness and generality.

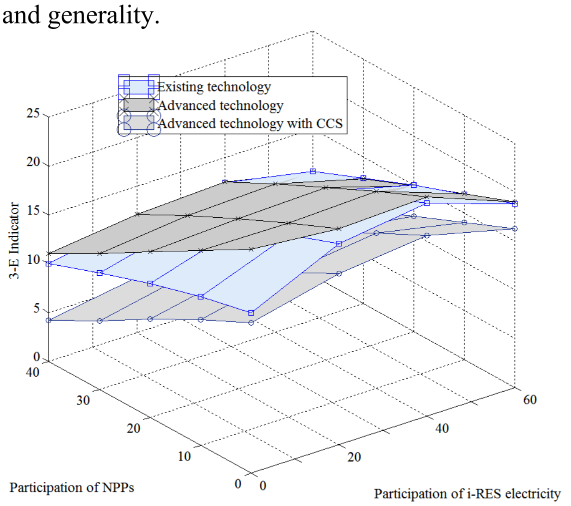

Figure 2: Graphical presentation of 3E Indicator as function of participation of i-RSE in total electricity generation, and NPPs in residual load generation.

The analyses are performed using analytical model described in (Grković, 2015) with necessary adoptions for the case. Basic data for the technologies considered in the analysis are also taken from reference (Grković, 2015). A more or less typical central European electric energy system is selected as the referent one and the load duration curves from Figure 1 are assumed as valid.

In Figure 2 are presented calculated values of 3E indicator for considered three mixes of electricity generating technologies. From the figure it follows that an increased share of electricity generated by NPPs in residual load domain, starting from zero value, enables decrease of 3E indicator, and thus improvement the electricity generating system regarding the complex of investments, CO_2 emissions and electricity generated. On the other hand, increased share of electricity generated by RES in total load domain, starting from zero value, causes increase of 3E indicator, and thus deterioration the electricity generating system, regarding complex of investments, CO_2 emissions and electricity generated.

Above relations are qualitatively very similar for all three considered electricity generating technology mixes. The amount of improvement obtained by increased participation of NPPs, which corresponds to the slope of the surface in the direction (see Figure 2) has the lowest value in the case of existing technology, while advanced technology with CCS causes the biggest gradients. In all three cases the best values of the 3E indicator are obtained with the highest considered value of 40% for nuclear electricity in residual load domain and 0% of variable RES. In our case the maximal value of the 3E indicator is obtained at RES participation of 40% and zero percent of nuclear participation. Generally, introduction of advanced technologies with CCS in the intermediate part of the residual load enable the best values of the 3E indicator, while the advanced technologies without CCS are giving the highest values of the 3E indicator.

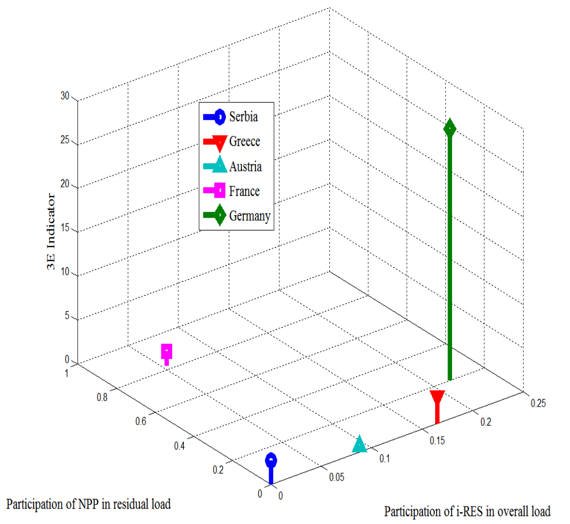

Figure 3: Graphical presentation of estimated values of 3E Indicator for selected countries.

Figure 3 shows calculated values of 3E Indicator as function of participation of i-RES electricity in overall electricity generation domain, and NPPs electricity in residual load domain for the group of selected European countries. For the purpose of this analysis in the data for the biomass are considered those related to investments and electricity generated, but not related CO_2 emissions, since the biomass is assumed as CO_2 neutral. The average values of CO_2 generation per unit of energy for different fuels are accepted according to (Kather, 2011), what is the same approach as in calculations of previous diagram. All assets are assumed as new one, i.e. no repayments of the investments are considered since there was lack of available data. Costs of the assets correspond to prices in 2016, according to (U.S. Energy Information Administration 2016; Breeze, 2010). 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 (https://transparency.entsoe.eu; http://www.iea.org/statistics/statisticssearch/; https://www.energy-charts.de/power; https://www.energy-charts.de/energy). The data are valid for the year 2015. The meaningful differences in the numerical values of 3E Indicator among considered countries can be recognized in Figure 3. This fact confirms previously introduced hypothesis that 3E Indicator has enough high sensitivity on the actual data in different countries, and thus is applicable for comparison of the actual situation in them, as well.

Much bigger value of 3E Indicator for Germany can be understood as that there is a big amount of electricity generating capacities, that cost a lot and that this fact has stronger impact on the 3E indicator than achieved CO_2 emissions. It looks as an "overinvestment" in the assets that operate producing energy in average of small number of hours per year. According to our calculation it is slightly under 3000 hours of work in full capacity per year. In contrary, small level of 3E Indicator for France points out that high participation of NPPs in residual load domain of about 80% enable better effect in CO_2 emissions with smaller amount of investments, resulting in longer average operation hours per year of the installed capacities. According to our calculation it amounts about 4450 hours of work in full capacity peer year. The other three countries do not have any NPP. However, the values of their 3E indicators are comparably good due to considerable amount of carbon free electricity generated by hydro power plants and i-RES. In Serbia about 28 percent of overall electricity generation comes from hydropower plants, in Austria such generation exceeds 63% percent, while in Greece carbon-free electricity amounts slightly over 40%. In these countries calculated average hours of work in full capacity peer year amount 4330, 3100 and 2944, respectively.

4 CONCLUSIONS

The paper presents the results of technology options research on the paths towards the carbon free electricity generation. For that three different technology mixes are considered. Each mix comprises i-RES and nuclear thermal power plants technologies as carbon free technologies, lignite fired technology in the base part, and CCGT technology which is aimed for pick part of the annual electricity load diagram. In addition first mix has existing hard coal fired technology without CCS, second mix in addition has advanced hard coal fired technology without CCS, while the third one has in addition advanced hard coal fired technology with CCS.

In order to enable quantitative measurements of the considered technology mixes, 3E Indicator is introduced. The Indicator comprises annual part of the investments in all electricity plants of the respected mix, annual amount of CO_2 emitted, as well as the annual amount of electricity generated. The principal application of the concept is described by appropriate model calculations for the general European conditions.

The results show that introduced 3E Indicator is sensitive on the types of technologies from which each mix is composed, as well as on the participation of carbon free technologies in overall electricity generation. This characteristic makes 3E Indicator suitable for analysis of the technological solutions within considered electricity generating system, and/or the country regarding investments in asset, CO_2 emissions and energy produced.

The analysis is exemplified by estimation of 3E indicator for the installed capacities and electricity generated in 2015 in the group of five European countries. The results show that the country with highest participation of NPPs and/or hydro power plants, and low participation of i-RES in electricity generation has the best i. e. the lowest value of 3E Indicator. On the other hand the country with highest participation of i-RES and low to moderate participation of NPPs and/or HPPs has the conceivably highest value of 3E Indicator. Two of the rest three countries have good values of 3E indicator due to high participation of hydro power in the technology mix, while third country has a combination of i-RES and hydropower.

Above results in principal can point out the path toward carbon free electricity generation. However, more detailed research is needed for drawing out the final and more detailed conclusions.

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