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MARGINAL SHARE OF RENEWABLE ENERGY SOURCES OF VARIABLE ELECTRICITY GENERATION
A Contribution to the Concept Definition

by

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Technology development is a keystone within the efforts toward enabling longer duration of the world fossil energy resources. The past development and the technologies applied, cause huge emissions of CO_2 that must be significantly reduced. Increased usage of renewable energy sources for electricity generation (RES-e) contributes essentially to the reduction of CO_2, but on the other hand, under current conditions of feed-in priority reduces also the market for the electricity from fossil fuelled power plants. The other possibility for reduction of CO_2 emissions is to apply carbon capture and storage technologies as a part of overall fossil fuelled power plants technologies.

A hypothesis presented in this paper is that there is a marginal share of RES variable electricity in overall annual electricity supply after which further increase of RES-e participation produces higher average electricity generated cost, than in the case of CO_2 emission reduction by applying carbon capture and storage technologies. The presented work confirms this hypothesis. Value of the marginal share depends to the price of RES-e feed-in. With the price span from 13.5 to 7.5 €c/kWh, the marginal share is under 50%.

Key words: *marginal share of RES variable electricity, energy technologies, carbon capture and storage, thermal power plants*

Introduction

Economic development forms certain need for energy that causes significant pressure on the energy resources to be consumed. To harmonize energy consumption and development, the welfare and the need for longer duration of fossil energy resources are not only big challenges, but also serious tasks. In solving the task several important problems are detected, like the problem of sustainable energy development [1] and the energy supply security [2]. As a tool for solving the tasks some authors have proposed the procedure for national energy system modelling [3].

Intensive energy consumption reproduces significant increase of the CO_2 content in the global atmosphere, and, as a consequence, contributes to the increase of the Earth average temperature. A significant part of the World public reacted on these facts and, as a result, the specific political decisions were brought on global level that were followed by appropriate leg-

islation in the most developed countries. Actual target is reduction of CO_2 emission for 20% up to 2020. However, the optimal final target is the zero emission level.

There are three options available for the fulfilment of such a plan: (1) an essential increase of renewable energy sources (RES) in the energy companies portfolios, (2) a reduction of CO_2 emissions from fossil fuelled power plants by applying appropriate technologies, and (3) improving economy toward a more energy efficient one.

There are several serious problems on the way to increase RES-e share. First is availability. The European conditions for utilization the generating capacity amount for photovoltaic plants 1000 hours per year, for wind on-shore 1300 to 2200 hours per year, for wind off-shore up to 3500 hours per year, but for fossil fuelled and nuclear power plants about 7500 hours per year [4]. This means that for the same energy production two up to five times more installed power capacities in RES than for fossil or nuclear power plants have to be build. Second, the convenient locations for wind generators are rather far from the centres of electricity consumption. Therefore, it is necessary to build corresponding transmission lines simultaneously with the wind farms. There are several estimates of the length of the transmission lines. Some estimates give their total length of 42000 km [5] and other present the 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 [6]. Building of such transmission lines needs funds and time and estimates of needed investments for Germany [6] amount to €20 billion. Estimates for grid improvements made by EPRI and cited in [7] amount to $500 billion. These lead to the very firm conclusion that energy problems of the World, and particularly Europe, are urgent [8].

A great share of the wind energy in total energy production requires big equipment production series, since the largest wind generator amounts now only to 6 MW, and this could enable a considerable price reduction of the single wind generator in the future (the learning curve effect). However, the question is if it is possible to fulfil the requested targets, since huge energy capacities have to be build, including the capacities for the replacement of the old plants. The total capacities of electricity production for the EU countries are estimated to be between 300.000 MW [9] and 476.000 MW in 2020 [10]. Both minimal and maximal figures are extremely large. For building these capacities great investments are needed. The estimates given in [11] are in the range of 200 to 300 billion euro.

Existing design of electricity market in Europe gives priority of RES variable electricity feed-in at the considerably higher price to the electricity generated by fossil and nuclear power plants. There is a certain part of the annual electricity consumption that is reserved and will be covered by RES electricity, while the residual part can be covered with the electricity produced by thermal and nuclear power plants. With increase of installed capacities of RES variable electricity feed-in decreases the residual load available for fossil fuelled and nuclear power plants and thus the annual operation time based on the installed capacities of these plants also decreases. As a consequence, the fix cost per kWh must be increased for unchanged level of the invested capital. On the other hand, higher participation of RES variable electricity also force fossil and nuclear power plants to operate at lower average loads, with more frequently load changes and with greater ramp rates. This contributes to the increase of the fuel cost due to lower average plants efficiency, and to the increase of the maintenance costs due to faster degradation of the material of the highest loaded components.

In such circumstances, and with current electricity market design, either the electricity price should be increased, or the profit of fossil and nuclear power plants must be decreased, if any. This stand point can be supported by the fact that electricity generating companies offer

even negative prices in extremely difficult situations and that was noticed in recent years for the first time [12]. As a further consequence, investors are getting out of the electricity sector in thermal and nuclear power plants [13]. So under the existing conditions of the present electricity market design, an increase of the average electricity price seems as burdened solution. The problem can be partly solved by appropriate grid extensions. For example, in [14] was drown the conclusion that revenues close to pre-VRE (variable renewable energy) levels can only be attained with substantial grid growth of 60%.

Reduction of CO_2 emissions from fossil fuelled power plants can be achieved by applying carbon capture and storage (CCS) technologies. In this case reduction of CO_2 emissions can be achieved without reduction of plants annual operating time and appropriate increase in the generating costs. On the other hand, CCS technologies are costly and energy intensive ones. However, a hypothesis can be put that there is a marginal share of RES variable electricity in overall annual electricity supply after which further increase of RES-e participation produces higher average electricity generated cost, than in the case of CO_2 emission reduction by applying CCS technologies. The analysis presented in this paper was performed in order to confirm this hypothesis. The research method and the obtained results are shown below.

Problem definition

Technologies for the future power plants

The following energy technologies can be considered for the future thermal power plants.

– Steam turbines that are used in plants with hard coal or lignite combustion technologies. Existing technologies enable plants efficiency of 43% in the case of lignite combustion and 46% in the case of hard coal combustion [15]. Advanced technologies based on advanced steam conditions level of 37.5 MRa/700 °C/720 °C can enable plants efficiency of 46% in the case of lignite combustion and 50 to 52% in the case of hard coal combustion [16, 17]. On the other hand, in nuclear power plants can be used only steam turbines with appropriate nuclear technologies, where electricity is generated with efficiency of about 33% but without any CO_2 emission.
– Open cycle gas turbines (OCGT) which use mostly natural gas as a fuel; dimensions and weight of these plants are considerably smaller than the previous ones, and therefore these plants are cheaper, regardless of the expensive materials and the technical solutions corresponding to very high process temperatures. Modern gas turbines operate with the temperatures of the combustion gases entering the turbine at the level of 1500 °C, that enables plants efficiency of about 40% [18].
– Combined cycle gas turbines (CCGT); they are very efficient and the world highest power plant efficiency (60%, measured during the acceptance test of a commercial thermal power plant) is obtained with such a technology [19].

For electricity production from RES the following technologies are in use nowadays.

– hydro power plants – run-off, hydro storage and pump storage,
– wind generators – on-shore (smaller air velocities) and off-shore (greater air velocities),
– photovoltaic – on roof and on the soil,
– thermal-solar plants, and
– biomass technologies with steam turbines and steam boilers with fix and fluidized bed combustion. Applications of gas turbine technology, as well as combined gas and steam technologies for the biomass are in the developing stage.

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According to the current practice, electricity produced by wind generators, photovoltaic and thermal-solar is not dispatchable, and therefore can be treated as variable electricity.

Each electricity generating technology is distinguished according to the necessary specific investments (€/kW), the efficiency of energy transformation, environment impact, as well as according to some other features (like maintenance cost, *etc.*).

The reduction of CO_2 emissions from fossil fuels fired power plants can be realized by (1) firing fuel with higher hydrogen content (natural gas), instead of fuels with higher carbon content (coal); (2) the application of clean technologies for CCS as a part of the power plants technologies; and (3) by increasing the efficiency of power plants.

The first option's effect is limited by available quantities of natural gas, as well as by its composition.

Today, three different groups of CCS technologies are developed, as schematically presented in fig. 1, according to [4, 20, 21]. Pre combustion technologies (1. in fig.1.) are based on processes of oxygen extraction from air, coal gasification processes, cleaning of the obtained gas, CO_2 separation, compression and transportation to the storage place, while the electricity is produced in combined cycle gas turbine plant fuelled with hydrogen rich fuel. Although the processes of coal gasification and gas refining are rather well known, it is necessary to improve the process of oxygen extraction, CO_2 extraction, as well as to improve hydrogen fuelled gas turbines [4, 20]. The energy consumption of such a technology is estimated from 5 to 8 percent points reduction of the plants efficiency [22]. It is expected that the commissioning of one 450 MW plant as a first plant with this technology will be done in 2014 [23].

In oxyfuel technologies (2. in fig. 1.) coal combustion is performed with pure oxygen with partial re-circulation of CO_2 and H_2O mixture, which is taken after flue gas cleaning facilities. Extracted CO_2 is compressed and transported to the storage [22, 23]. The estimated efficiency reduction due to additional energy consumption of this technology amounts 8 to 12 percent points [22].There are 6 test facilities already built in the world according to such a technology, and for the next 9 facilities the building is at the planning stage [23]. Building of the demonstration plant where this technology will be applied is also planned at the site Janeswelde in Germany [22, 23].
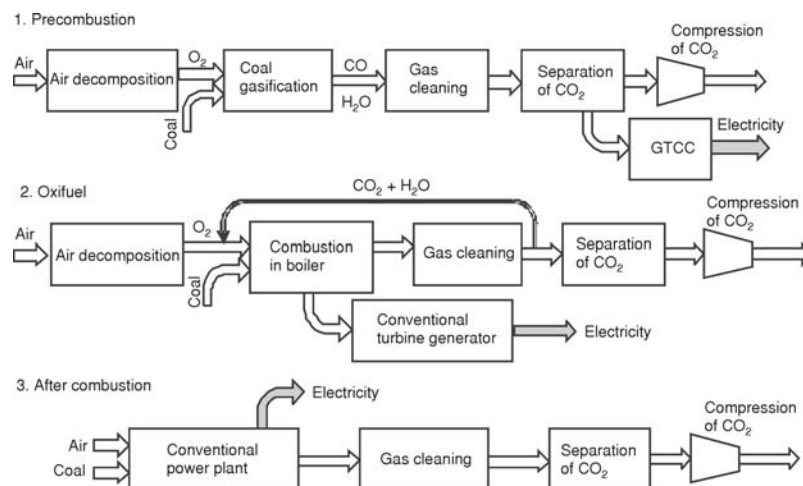

Figure 1. Technologies for carbon capture and storage schematically presented (according to [5, 22, 25], reshaped)

Technologies for carbon capture after combustion (3. in fig. 1.) presume conventional thermal power plants with added facilities for flue gas cleaning, as well as for CO_2 separation. The developments of several technical solutions for flue gas cleaning are in progress [5, 22] and promising are those that use absorbers for flue gas cleaning [4]. The estimated efficiency reduction due to energy consumption for these technologies amounts 8 to 12 percent points [22]. There are 25 test facilities already built in the World according to such technology, and for the next 33 facilities the building is at the planning stage [24]. The use of the membrane processes, instead of absorption, could contribute to a significant reduction of energy consumption.

Post combustion carbon capture technologies look very promising for retrofitting of existing power plants. Even for the new power plants capture readiness design that enables later retrofit is attractive. On the other hand, some analysis [26] concludes that such an approach is still questionable.

Each increase of the thermal power plants efficiency as a consequence is followed by the appropriate reduction of CO_2 emission. Combinations of CCS technologies with advanced highly efficient power plant technologies could enable good results in the removal of CO_2 with acceptable overall plant efficiency. For example in [22] is forecasted that CO_2 emission from the coal fired power plant can be reduced from 750 g CO_2/kWh to 100 g CO_2/kWh, but together with a net efficiency decrease from 46% to 36%.

The analysis of marginal share of RES-e presented in this paper is performed with the technologies shown in tab. 1 [17].

Table 1. Technologies considered in the analysis of marginal share of RES-e [19]

Fuel/Technology	Efficiency [%]	Specific cost [€/kW]
Lignite/Steam turbine, existing	43	1725
Lignite/Steam turbine, advanced	46	1950
Hard coal/Steam turbine, existing	46	1500
Hard coal/Steam turbine, advanced	50	2250
Natural gas/CCGT	60	400
Lignite/Post combustion CCS	10[*]	800
Hard coal/Post combustion CCS	10[*]	600

* The value represents reduction of plant's efficiency in percent points

Scenarios for covering of the residual load

Since the RES with variable load (photovoltaic and wind generators) are not dispatchable, the annual available space in electricity market for fossil and nuclear power plants (as dispatchable ones) is determined by the residual load duration curve. The curve is obtained by subtracting the energy produced by RES-e from the energy defined by the annual load duration curve, and therefore depends on the percentage of annual RES-e in-feeds. Examples of the residual load duration curves for 20%, 40%, and 60% of RES-e in-feed according to [27] are presented in fig. 3, while the curve for 80% is our estimate. Similar residual load duration curves for 23.6%, 33.8%, 50.0%, 60.2%, and 75.5% of annual RES-e in-feeds are presented and discussed in [28].

Dispatching of the dispatchable electricity generating plants in residual load region is performed according to the merit order. In order to simplify the problem, it is supposed that in the base part of the load duration curve electricity is produced by lignite fired power plants (since they have, together with nuclear plants the most favourable electricity costs), in the middle part electricity is produced by hard coal fired power plants, and in the peak part electricity is produced by gas fired CCGT plants.
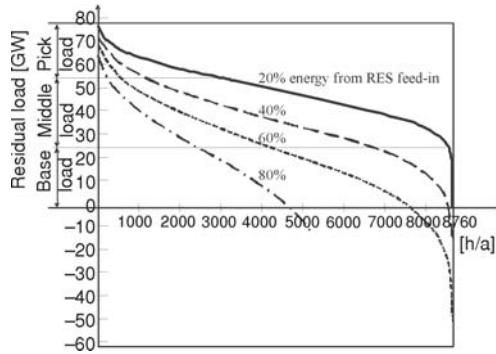
Figure 2. Residual load duration curves for different RES energy in feed (for 20, 40, and 60% according to [27]; and for 80% own estimates)

The average electricity generating costs as function of the share of RES electricity feed-in in total electricity generation are analysed for six different scenarios of electricity generation in residual load area together with considered technologies. Each of them is considered with RES participation in the total electricity generation as the independent variable. The overview of selected scenarios and considered technologies is given in tab. 2.

In the first scenario (1 in tab. 2.), the total capacity of lignite fired power plants is kept at the same level as at the starting RES-e participation level, while coal fired power plants capacities are reduced in accordance with RES-e in-feed increase. The reduction can be performed by decommissioning the old plants, followed by slower commissioning the substituting capacities. In this scenario there are two variants of the technology mix for electricity generation, 1A and 1B in tab. 2. The assumption for variant 1A is that the base and medium parts of the residual load are covered by existing technology for lignite fired plants and existing technology for hard coal fired plants, respectively, while the peak part is covered by natural gas and CCGT technology. In variant 1B for base and medium parts of the residual load advanced technology for lignite fired plants, and advanced technology for hard coal fired plants, respectively, are assumed, while for peak part is covered again by natural gas and CCGT technology.

Table 2. Overview of selected scenarios and considered technologies

Scenario	Capacity reduction due to RES-e in-feed increase	Base residual load covered by	Medium residual load covered by	Peak residual load covered by	Presence of CCS technologies
1A	Hard coal fired plants	Lignite/ existing technology	Hard coal/existing technology	Natural gas/ CCGT	No
1B	Hard coal fired plants	Lignite/advanced technology	Hard coal/ advanced technology	Natural gas/ CCGT	No
2A	Lignite fired plants	Lignite/ existing technology	Hard coal/ existing technology	Natural gas/ CCGT	No
2B	Lignite fired plants	Lignite/advanced technology	Hard coal/ advanced technology	Natural gas/ CCGT	No
3C	Max RES-e feed in 20%	Lignite/existing technology	Hard coal/ existing technology	Natural gas/ CCGT	Yes
3D	Max RES-e feed in 20%	Lignite/advanced technology	Hard coal/ advanced technology	Natural gas/ CCGT	Yes

In the second scenario (2 in tab. 2), the total capacity of lignite fired power plants is reduced, but the total capacity of the hard coal fired power plants is kept at the same level as at the starting RES-e participation level. There are also two variants of the technology mix for electricity generation in this scenario. The assumption for variant 2A is that the base and medium parts of the residual load are covered by lignite fired plants and existing technology for hard coal fired plants, respectively, while the peak part is covered by natural gas and CCGT technology. In variant 2B for base and medium parts of the residual load advanced technology for lignite fired plants and advanced technology for hard coal fired plants, respectively, are assumed, while the peak part is covered again by natural gas and CCGT technology.

In the third scenario the participation of RES-e stays at the level of 20% and the reduction of CO_2 emission is provided by applying clean CCS technologies as a part of the overall power plants technology. Two technological variants are considered for this scenario. The existing technologies for lignite fired and hard coal fired plants both together with CCS equipment and CCGT technology for peak load (variant 3C) and advanced technologies for lignite fired and hard coal fired plants both together with CCS equipment and CCGT technology for peak loads (variant 3D).

Model for calculation of average production costs

The average production cost for annually generated electricity in residual load part is calculated according to the equation:

$$C_{rlp} = \frac{E_b C_b + E_m C_m + E_p C_P}{E_b + E_m + E_p} \tag{1}$$

While the average production cost for the total annually generated electricity is calculated according to the equation:

$$C_{tot} = \frac{E_b C_b + E_m C_m + E_p C_P + E_{RES} C_{RES}}{E_b + E_m + E_p + E_{RES}} \tag{2}$$

Electricity generated in base, medium and peak parts of the residual load, as well as those generated by RES is calculated according to the residual load duration curves for different RES energy in feed presented in fig. 2, assuming that it represents an average year. Cost of electricity generation for each considered technology is calculated as sum of fix and variable costs:

$$C = C_{fix} + C_{var} \tag{3}$$

Fix cost comprise capital cost, taxes, and insurance and is calculated according to the equation:

$$C_{fix} = c_{in} P_{egr} (a + s + v) \tag{4}$$

Variable cost comprises fuel cost, cost for certificate for CO_2 emission and cost for CO_2 compression and transport (when it occurs), and is calculated according to the equation:

$$C_{var} = \frac{E_{cegt}}{\eta_{egt}} \{ C_{fl} + p[(1-v)C_{ceCO_2} + vC_{ctCO_2}] \} \tag{5}$$

Last member in above equation is equal to zero for the scenarios 1A, 1B, 2A, and 2B, since there is no compression and transportation of CO_2 and therefore the rate of CO_2 capture, v, equals zero. E_{cegt} refers to the electricity load covered by the considered electricity generating technology.

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Share of variable renewable energy sources of variable electricity generation in overall electricity generation is defined as:

$$\gamma = \frac{E_{RES}}{E_{tot}} \tag{6}$$

The marginal share of renewable energy sources of variable electricity generation is defined as those for which is the average production cost for the total annually generated electricity with RES equal to the average production cost for the total annually generated electricity with thermal power plants technologies together with CCS technologies. In mathematical form this definition can be expressed as:

$$\gamma_M = \frac{E_{RESM}}{E_{tot}} \quad \text{for} \quad C_{tot}(RES) = C_{tot}(CCS) \tag{7}$$

The rate of CO_2 capture in the calculations is assumed to be 0.866, which is slightly below 0.90, the value given in the literature [5, 12]. The expenses for CO_2 compression and transport are assumed at the level of $30€_{2010}/tCO_2$, which is the upper value from the estimation given by [24]. Availability of lignite fired and hard coal fired plants is assumed 85% for operation in residual load when RES-e feed-in is 20% and lower, and 90% in the case of operation in residual load when RES-e feed-in is above 20%.

The investment costs presented in tab. 1 are used for the analysis. Exceptionally, the advanced hard coal technology investment cost of 1875, 1750, and 1650 (in $€_{2010}$) are used for the share of variable renewable energy sources of 0.4, 0.6, and 0.8, respectively. In this way, the learning curve effect is taken into account, according to [17].

The fuel prices for considered share of variable renewable electricity in the overall generated electricity are assumed according [17] and presented in tab. 3. The estimated prices for CO_2 certificates in the same period are also taken in accordance with data presented in [17] and presented in tab. 3. However, these values are 4 to about 7 times greater than those presented in [14] as an all-time low in 2012. Supposed financing conditions are: loan with an interest rate of 7.5% and a return period of 15 years. An overview of the costs for considered fuels, as well as for CO_2 certificates and for CO_2 compression and storage is presented in tab. 3, based on [1, 17].

Table 3. Fuel costs in $€_{2010}$/MWh and of CO_2 related costs in $€_{2010}/tCO_2$, based on [1, 17]

Share of RES-e	0.2	0.4	0.6	0.8
Lignite	1.4	1.4	1.4	1.4
Hard coal	13.4	13.8	14.3	14.7
Natural gas	28.1	30.1	32.1	34.1
CO_2 certificate	25	35	40	45
CO_2 compression and storage	30	30	30	30

Results and discussion

The cost analysis is performed based on the mentioned technologies for assumed scenarios for residual load covering and cost calculation method. Necessary costs levels are based mainly on the data from cited literature. As the parametric variable the share of variable renewable energy sources in overall electricity generation is selected, as defined by eq. (6). The main objective is to investigate existence of the marginal share of variable renewable energy sources as defined by eq. (7). Obtained results are presented as follows.

First, the influence of the share of variable renewable energy sources on the average electricity production cost in the residual load domain was analysed. The results are presented in fig. 3. It can be seen that an increased participation of variable renewable electricity in the total annual electricity consumption causes significant increase of the average electricity production costs in the residual load domain. The largest part of the increase is the increase of fix expenses due to reduced production and volume of sales of thermal power plants. The smaller part of the average electricity production costs increase is the increase of variable costs due to assumed increase of the fuel price and CO_2 certificate price.
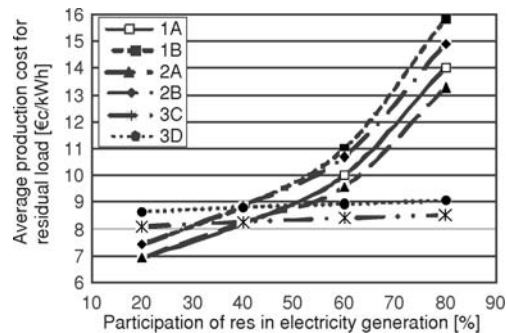

Figure 3. Average production cost in residual load for supposed dynamic of variable RES feed-in increase and for six considered variants

Calculation results shows that the variants with CCS technologies are costly favourable if more than 40% of the consumed electricity comes from RES feed-in. The conclusion is valid for both the existing, as well as for the advanced energy transformation technologies. The difference in the electricity production cost between existing and advanced technologies is not great, although the investment costs of advanced technologies are 50% greater than of the basic ones. The above fact can be explained by the appropriate difference in the plants efficiency, as well as by the severe economic conditions for operation in the residual load domain.

Understandably, the variants with existing technology for fossil fuel transformation are costly favourable compared to the advanced ones. Also, the scenario with a reduction of lignite fired power plants capacities with increasing variable renewable electricity production enables better prices. This can be explained by higher fix cost of this type of power plants, compared to the hard coal fired ones.

The above cost simulations did not include additional costs caused by plant's operation on lower load; more frequent shut downs and starts, the faster ramp load changes as well as the possible reduction of plant's life due to such operations. The results presented in fig. 3, also indicate severe economic conditions for thermal power plants operation in residual load domain when share of renewable electricity generation is drastically increased.

The influence of the share of variable renewable energy sources on the average annual electricity production cost is analysed and the results are presented in fig. 4. The increase in the average production cost for the entire annual electricity production is smaller, due to the reference price of the variable renewable electricity of 13.5 €c/kWh. The cost advantage of CCS technologies starts from nearly 30% of the share of variable RES electricity and this is in fact the searched marginal share. The average cost is somewhat higher, compared to those for the residual load domain, due to the reference price of variable RES electricity of 13.5 €c/kWh.
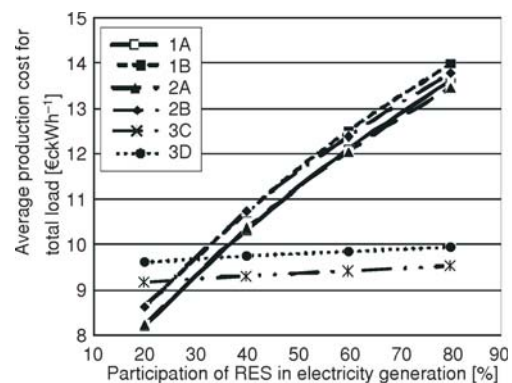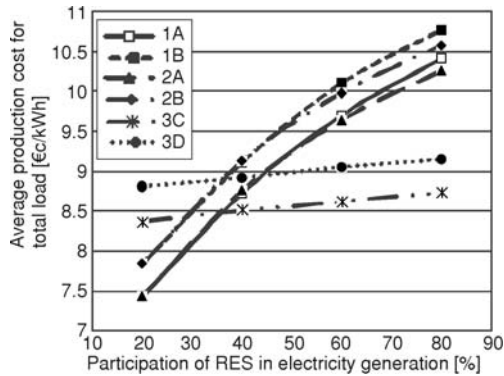

Figure 4. Average production cost in total load domain as function of share of variable renewable energy sources in overall electricity generation. The reference price of variable RES-e feed-in is 13.5 €c/kWh

Figure 5. Average production cost in total load domain as function of share of variable renewable energy sources in overall electricity generation. The reference price of variable RES-e feed-in is 9.5 €c/kWh
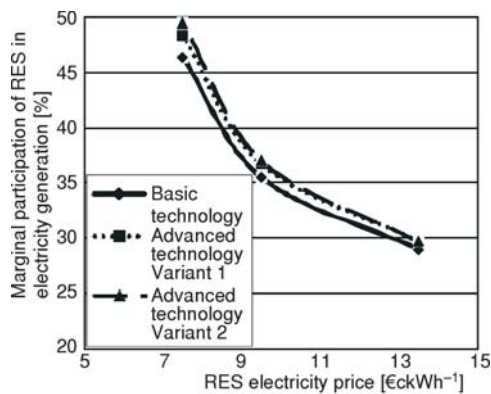

Figure 6. The influence of the reference price of variable RES-e feed-in on the value of marginal share of variable RES electricity generation
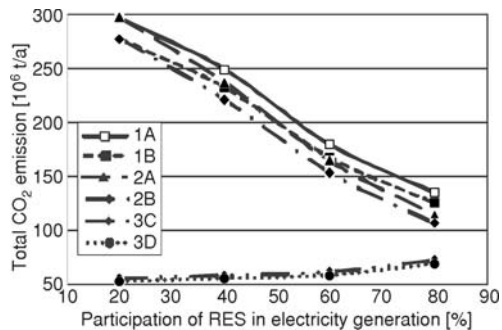

Figure 7. Calculated CO_2 emissions for six considered variants

Calculations of average annual electricity generating cost with reference price of 9.5 €c/kWh for variable RES electricity feed-in are also performed. Obtained marginal share of variable RES electricity generation is 37% for advanced technologies, and somewhat lower for the existing technologies (fig. 5). These values are somewhat higher than in the previous case. In this case, the difference of average prices obtained for the basic technologies (variants 1A, 2A, and 3C) and for the advanced ones (variants 1B, 2B, and 3D) is also greater than in the previous case.

Lower reference price for variable RES electricity feed-in enables higher values of marginal share. However, even with reference price of 7.5 €c/kWh for variable RES electricity feed-in, the marginal share of RES electricity generation does not exceed 50% of total electricity generation, as can be seen in fig. 6.

Considered technology variants are also compared regarding the total CO_2 emission, which follows the same amount of electricity generation. The calculation results are presented in fig. 7. The variants with CCS technologies and limited participation of variable RES electricity produce, for the same amount of generated electricity, considerably smaller emissions than the other ones. However, CCS technologies would have to operate perfectly to achieve such effects, as noticed in [29, 30].

Conclusions

The research is performed to investigate existence of marginal share of variable renewable energy sources that borders the area where is price favourable CO_2 to be removed by CCS technologies, instead further to increase feed-in of variable electricity generated by RES. The analysis has considered current, as well as advanced technologies for transformation of fossil fuel into electricity, since there are significant possibilities for further advancement of these technologies. For the optimal results the technologies should be harmonically mixed. This conclusion corresponds to those presented in [31].

Technologies for CCS are still in the development phase. Although the first commercial facilities are expected within this decade, a wider application of the technologies can occur after 2020 [32]. However, it is very important that these technologies become mature at the beginning of twenties.

The use of RES is important for achievement the European targets in environment protection and CO_2 emissions reduction. However, variable RES like wind and solar are not despatchable and their wider use need to be adequately managed.

In case of a large percentage of variable RES electricity feed-in (over 20%), as well as its feeding priority, the annual electricity production of fossil fuelled power plants becomes significantly lower, compared to the conditions where the RES feed-in is low. The results of the cost analysis are obtained for the residual load duration curves taken from literature and assumed as representative for an average year. An electricity generation park is simplified and reduced to only three types of the technologies based on the fossil fuel (lignite fired, coal fired, and natural gas fired), and thus can be treated as virtual. However, all the plants characteristics, like the investment costs, efficiencies and others correspond to the real ones and their accepted values are conservative. The results show that:

- Created scissors of the electricity production costs and the actual selling prices seriously threat to cut down the profit of the utilities with technologies based on the fossil fuel.
- There is certain value of RES variable electricity feed-in share in overall electricity sale – the marginal share, that borders the area where the cost of removal of CO_2 by CCS technologies is favourable compared to the increase in-feed of variable electricity produced by RES.
- The existence of the marginal share clearly confirms the hypothesis.
- Value of the marginal share depends to the price of RES-e feed-in. With the price span from 13.5 to 7.5 €c/kWh, the marginal share is under 50%.

Within the analysis is not covered additional costs related with large RES feed-in, like necessary grid extension and smart grid technologies. However, taking into account and these costs can cause reduction of calculated values of marginal share of RES of variable electricity generation.

In many cases in the base part of the residual load electricity is produced, beside lignite fired plants and with some other type of technology like nuclear one. Electricity from the later technology has about 20% higher costs, than those from lignite fired plants [4]. Thus in the case of equal electricity generation from nuclear and lignite fired power plants and base load energy participation with 37% in total electricity supply, the overall calculated electricity cost can increase for about 4%. In the case of usage of hard coal technology instead of nuclear in the base part of the residual load domain and remaining unchanged the previous conditions, the increase of calculated total electricity cost is under 4%, since the electricity cost from hard coal plant is higher for about 15% than those from lignite fired one [4]. In the case that in the medium part of the residual load second technology is included, like CCGT, more or less similar relations can be obtained.

In the case of electric energy system with residual load duration curves different from those in fig. 2, the value of the marginal share is expected to be differing from the value obtained in the paper. However, each electric energy system must be treated as specific case for which above procedure for determination of marginal share of RES has to be applied.

Having in mind above-mentioned the forecasting of the future conditions, both operational and economical becomes an important issue for obtaining reliable results. There is some risk connected with misforecasting. However, it lies in the level of the risk connected with procedures for almost all forecasting of energy issues. On the other hand risk of the application of

CCS technologies as emerging technologies is very specific problem and can be treated in a separate research.

Pump-storage plants as a mature energy management technology can be used for meeting great changes of the power demand in the system, with minimum impact. However, their economic compatibility is determined by their specific investment costs and with the need of the cheapest electricity for pumping [27, 28]. Up to now the cheapest electricity was that from lignite fired and nuclear power plants. On the other hand, detailed analyses show that in the systems with large RES feed-in, pump-storage plants have difficulties to provide all the necessary variable power [12]. Therefore, to allow use of electricity produced by photovoltaic devices and wind generators in surplus periods the grid extension is more frequently considered

Although obtained quantitative results are affected by the introduced simplifications, the qualitative relations can have a broader meaning. However, the value of marginal share of RES variable electricity feed-in can be determined for each of the analysed electricity generating system.

As the result of the above presented analyses, energy technologies based on fossil fuel, combined with CCS technologies represent the acceptable solution for future efficient and environment friendly electricity generation.

Nuclear power plants have no CO_2 emission. This fact, as well as the low fuel cost, or the low cost of their electricity, makes them in general a real option for electricity generation.

The optimal technology portfolio of energy companies and even of the whole electricity generating system in principle can be defined, and thus enabled a better cost, as well as overall environment effects.

Nomenclature

a – annuity factor, [year^{-1}]
C – electricity generating cost, [€c/kWh]
c_{in} – specific investment cost, [€/kW]
E – generated electricity, [kWh]
P – power plants capacity, [kW]
p – specific yield of CO_2, [tCO$_2$kWh^{-1}]
s – annual amount of all taxes, [year^{-1}]
v – annual amount of insurance, [year^{-1}]

Greek symbols

γ – share of variable RES electricity, [–]
ν – rate of CO_2 capture and storage, [–]

Indexes

b   – base
ceCO$_2$ – certificate for CO_2

c egt – covered by electricity generating technology
ctCO$_2$ – CO_2 compression and transportation
egt – electricity generating technology
fix – fix
fl – fuel
in – investment
m – medium
p – peak
RES – variable renewable energy source for electricity generation
rlp – residual load part
ro – residual load
tot – total load
var – variable

Acknowledgment

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