Circular economy indicators in power sector

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***Abstract*— The process of transformation of a linear economy into a circular economy requires monitoring and supervision of progress, therefore in this work, indicators of the circular economy were proposed for example types of power plants based on the Polish energy system and its needs. An attempt was also made to analyse the transformation inside the example power plants- Belchatow Power Plant and to compare the transformation process among different coal-fired power plants. The analysis shows that a positive change has been taking place in the energy sector for years, but it is hard to clearly state whether a given power plant works in accordance with the concepts of circular economy. In many respects specific, shared data is missing, and the coefficients for which calculations are possible do not give the full picture of the situation. For this reason, in the discussion summarizing all the work, further steps and necessary measures were recommended to effectively monitor the transformation towards a circular economy.**

Keywords- ***circular economy, energy sector, coal power plants, circular economy factors, monitoring of the circular economy.***

I. Introduction

Negative aspects of climate change and providing safe and generally available energy are the key challenges that face the future development of EU energy systems. The security of energy supply dilemma arises from issues such as energy and material scarcity, waste generation and being dependent from import. The difficulties mentioned above can be mitigated by developing economy model towards low-carbon, sustainable and resource-efficient one. Therefore, recently, the circular economy (CE) ideas have drawn attention of many experts worldwide. As it is a new concept, it has been explored by researchers to obtain its sustainable formula but the implementation of its concept it is still not an easy task.

There are required tools and methods to support the circular economy goals and monitoring the change from linear economy to circular one. Hence, many attempts to develop circular indicators was made in last years (Saidani et al., 2019). On the other hand, as the idea of CE is still on its early level, further researchers and developing of CE indicators to evaluate the CE performance are needed, especially in micro scale (Elia et al., 2016).

Circular economy and its approach of closing the loop corresponds assumptions of low-carbon model, sustainable and resource-efficient economy. Adequate integrated waste management system has a very important role here. Not only material-wise but also material recovery and from energetic point of view, using energy from wastes. As presented in the article Tomić and Shneider 2018, energy analysis as an approach to sustainable development of products and systems relating to primary energy consumption is a valid concept.

By combining the two approaches, the material and energy impact of the "closing the loop" process can be assessed by considering how much the energy from the recovered materials can be reduced. The analysis carried out in the article shows the potential of energy recovery and its enormous impact on meeting energy needs. In 2020/2030, it has the ability to meet 50/60% of the energy needs of a given city. Moreover, in 2030, 38% of waste can meet about 50% of energy needs. This shows that the capacity of energy systems through material recycling can reduce embodied energy of recycled materials by 11-67% which can be key in achieving circular economy and "closing the loop" (Tomić and Schneider 2018).

The CE approach and developing economy model towards low-carbon and resource-efficient influence whole energy sector but especially coal power plants, which are one of the biggest greenhouse gases emitters (about 350 mln Mg of CO_2 eq), together with other coal combustion products (about 20 mln Mg) out of which 35% is storage (Bielecka et al., 2018). As the transformation is not obvious and at the beginning easily visible, there exists a need to develop the method to measure the progress towards CE. Even though, its definition is not specified and have unclear boundaries, evaluation of indicators to monitor the progress is necessary (Geng et al., 2012).

The aim of this work is to identify, analyze and propose circular economy indicators for power sector that could support the transformation towards a circular economy starting with the specific subsector of energy production. The scope of the test application of the indicators was narrowed down to Poland and sample power plants.

The major steps, that was followed in further parts of this work are:

1. First, preparing the theoretical background about work issues, circular economy itself, already defined circular economy indicators and Polish energy marker as a base for further analysis,
2. Conducting the critical analysis of indicators reported by companies and proposing indicators for micro scale of power sector (coal power plants),
3. Proposal of the method to evaluate the progress

toward circular economy based on proposed indicators within one power plant,

4. Proposal of the method to evaluate the progress toward circular economy based on proposed indicators among different power plants,
5. Calculation of recommended indicators for sample power plants and applying evaluation methods,
6. Discussion the results and further recommendations.

II. State of knowledge

A. Circular economy

Circular economy is a model of economic development that is based on building economic, environmental, and social capital. This results in a gradual separation of economic activity from the consumption of limited resources of primary raw materials. Along with maintaining performance, it implies meeting other assumptions, such as (The Council of Ministers, 2019; Ellen MacArthurFoundation, 2013):

1. maximizing the added value of raw materials/ resources, materials, and products,
2. minimizing the generated waste and managing it in accordance with the hierarchy of procedures.

Circular economy means not only reducing the negative effects of a linear economy, but also a systemic change that generates both economic and business opportunities. Additionally, it provides environmental and social benefits. Its concept assumes effective global and local action of small and large companies or organizations and individuals (Bielecka, 2017).

The designed circular economy model distinguishes between technical and biological cycles. Biological cycles consume materials of biological origin which, through many processes, are designed to recharge the system. In the technical cycle, products are recovered and restored through reuse, repair, remanufacturing or recycling (Ellen MacArthur Foundation, 2013). The energy industry can fit into both cycles. In addition, since a significant part of energy resources is imported, an important issue for many countries is to ensure security of supply, hence it is important that micro-scale activities in the field of circular economy are correlated with policies and challenges applicable to the entire sector and economy.

Achieving the goals of the circular economy requires significant technological and organizational changes and the development of a set of indicators to assess:

1. progress in transformation towards circular economy,
2. impact on socio-economic development at the mesoeconomic and macroeconomic level.

Identifying and studying quantitative and qualitative progress is a complex and multifaceted task, relating to the implementation of new business models that cover the entire value chain - from eco-design to residual waste management. The transformation towards circular economy is not limited only to specific materials or sectors, but also concerns the development of indicators monitoring economic, environmental and social changes.

Circular economy is a cross-sectoral concept with a wide spectrum of thematic categories, including economic growth, materials management, the amount of generated and manageable waste, the quality of life of the society, the possibility of implementing eco-innovations, the development of IT technologies, etc. The European Commission and some international organizations and entities, e.g., OECD, World Bank, Ellen MacArthur Foundation, have already developed numerous sets of indicators, which, however, require improvement and adjustment to priority objectives. With reference to the definition of circular economy, the following are usually assessed: the consumption of materials and raw materials, waste management and activities around eco-innovation, compared to the amount of gross domestic product (GDP) generated (Kulczycka, 2020).

The concept of circular economy, also known as the economy of sustainable development, was created to change the current model of linear economy, which significantly exploits the environment, leading to its degradation. The linear model has a unidirectional flow of materials. Raw materials are transformed into products and then ultimately into waste (Elia *et al.*, 2017).

What is more, the circular economy concept is based on the use of recycling and re-use of materials and the reduction of raw materials and energy consumption, as well as the introduction of new business models. By combining these activities, circular economy also implements the principles of sustainable development in three dimensions: economic, social and environmental (Korhonen et al., 2018).

B. Energy key sector

Energy is considered by the European Union as one of the priority areas and is listed in the Europe 2020 development strategy as one of five, which is expected to achieve a 20% share of energy from renewable sources (RES) in the total amount of energy consumed in Europe and to increase efficiency energy use by 20%. In addition, the Europe 2020 strategy covers other areas, such as improving the security of supply, ensuring the competitiveness of the European economy and the availability of affordable energy. These goals, although established a few years earlier, are updated and verified. They directly or indirectly affect the issues discussed in circular economy, e.g., reducing the amount of non-renewable raw materials used in energy production processes and the amount of waste generated (European Environmental Agency, 2019).

The European Environment Agency monitors the progress in meeting the above requirements by European countries, updates and publishes each year a set of energy and environmental indicators together with assessments of the expected environmental benefits and the pressure exerted on the environment with a different share of energy from RES. The published indicators allow to determine many important aspects also in terms of circular economy. These include, for example, the pace of introducing technologies to produce energy from renewable sources, the rate of increase in energy efficiency, energy consumption, and the impact of energy consumption on the environment.

The published indicators for the Member States and the entire EU include:

- final energy consumption by sector and fuel,
- primary energy consumption,
- final energy consumption by sector and fuel,
- share of renewable energy in gross final energy consumption,
- progress in the field of energy efficiency,
- efficiency of conventional electricity and heat production.

These are indicators directly related to the energy sector, but several of them can also be used to measure the transformation towards circular economy. Data such as primary energy consumption and the share of renewable energy in gross final energy consumption are often reported on a smaller scale by companies in CSR reports or integrated reports. Some of them are consistent with the indicators proposed by the European Commission for monitoring circular economy in 2018, which are analyzed for individual Member States and are constantly updated (The European Commission, 2020; Pottin, 2017; The European Commission, 2018).

In 2019, the European Commission announced a communication on the European Green Deal. It is a new growth strategy that aims to transform the EU into a fair and prosperous society, living in a modern, resource-efficient and competitive economy that will achieve net zero greenhouse gas emissions in 2050, and where economic growth is decoupled from natural resource use. This strategy applies to virtually all sectors of the economy, including the energy sector (Tomić and Schneider, 2018).

In the communication, the European Commission also addresses the topic of clean, affordable, and safe energy. Since more than 75% of greenhouse gas emissions in the EU come from the production and use of energy, energy efficiency and renewable energy sources must become a priority in the development of this sector of the economy with the simultaneous withdrawal of conventional energy. Intelligent integration of renewable energy sources, energy efficiency and other sustainable solutions will allow to reduce emissions in the most beneficial way (The European Commission, 2019).

Ensuring uninterrupted supplies of raw materials is an important factor in the development of the energy sector. Currently, European countries must import more than 50% of metal ores and mining energy resources. It is expected that Europe's independence from these raw materials will continue to decrease, and in 2030 the EU is to obtain only 12% of crude oil, 19% of gas and 34% of coal from its own sources. It should also be remembered that the extraction of raw materials itself is burdensome for the environment and is associated with significant emissions and other hazards (Priyadashini and Abhilash, 2020).

In Poland, due to the depletion of non-renewable resources, the increase in their prices and the growing dependence on their import, many activities influencing the decisions of entities are taken at the central level. Supporting the transformation towards circular economy is an essential element of creating a low-emission, resource-efficient, innovative, and competitive Polish economy (The Council of Ministers, 2019; Bachorz, 2017).

According to the rules dictated by the circular economy, all materials should be reused after their recovery and recycling (Bist et al., 2020). In addition, it is important to implement this approach already at the planning stage, to use innovative solutions such as the inclusion of photovoltaic panels in roofing or the construction of acoustic screens by motorways (The European Commission, 2020). Efficient use of raw materials and stopping them from wasting them may reduce the level of energy demand (Bukowski and Sznyk, 2019).

Another important element connecting circular economy, energy policies and strategies and the activities of entities in the energy sector is the minimization of generated waste. In Poland, the power industry is based mainly on the combustion of hard coal and lignite. During combustion, harmful gases and also the so-called combustion by-products, i.e., ashes, slags and dust. Although they are a source of many minerals, their potential is unfortunately not used.

Meanwhile, their further use in industry could significantly contribute to the transformation towards circular economy, meeting the assumptions about the use of waste as raw materials for re-production. In 2019, the adopted circular economy roadmap proposed several actions, including:

- analysis of the potential and proposed legislative changes aimed at increasing the economic use of combustion by-products,
- development of guidelines on Waste-Free Coal Energy aimed at minimizing the environmental nuisance associated with coal mining and the production of electricity and heat from its combustion.

The aim of these activities is to implement new solutions increasing the possibilities of using coal combustion products (CCPs) through cooperation with the science sector and to define quality requirements for by-products, thus enabling their further use, among others as components of embankments and concretes (The Council of Ministers, 2019; Bochenek, 2018)

C. Composition of Polish energy sector

The Polish energy system is based mainly on hard coal and lignite, which accounted for 70% of installed capacity in Poland in 2019. If we look at the capacity installed in the Polish power system in the last decade, the prevailing trend can easily be noticed. A slight increase in power plants based on hard coal, natural gas, and a significant increase in renewable energy sources. In total, more than 10 GW of power has been added to the system since 2010. The change of installed capacity in Poland between 2010 and 2019 is presented in the Figure 1 below.

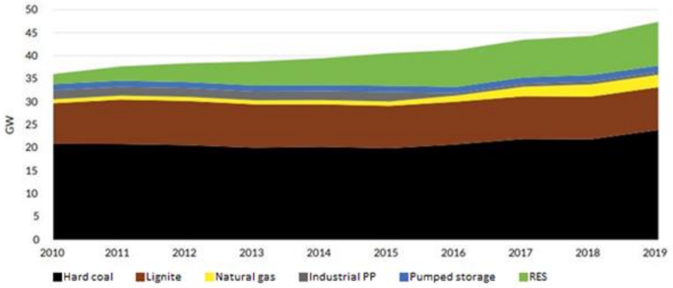

Figure 1. Change of installed capacity in Poland 2010-2019

Source: Macuk R., 2020

Despite the increase in installed capacity, the sheer amount of energy produced annually in 2019 remained at the same level as in 2010 with slight fluctuations in the meantime. There is a noticeable difference in the composition. While the share of hard coal remained at the same level, the share of lignite significantly decreased (around 10 TWh). On the other hand, the production from renewable energy and natural gas increased, which was certainly influenced by regulations and laws that came into force and forced to invest in this branch of energy. The change of total electricity produced between 2019 and 2019 is shown in Figure 2 below.

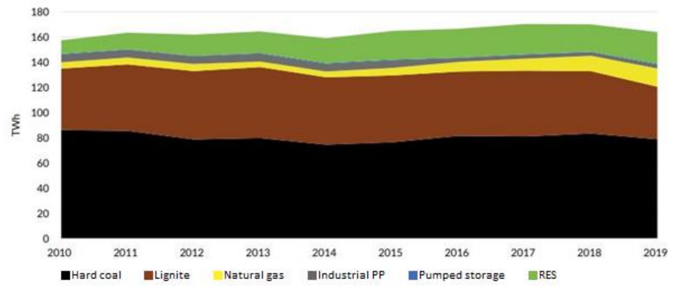

Figure 2. Change of total electricity production in Poland 2010-2019

Source: Macuk R., 2020

Greenhouse gases, in 2018 their emissions (mainly CO_2, methane and nitrous oxide) remained at the same level as in the previous years and amounted to 412.5 million Mg of CO_2 equivalent. Both in the Polish electricity and heating sectors, despite many apparent measures aimed at reducing greenhouse gas emissions, there are no real effects (Macuk R., 2020).

The above description of the Polish power system shows how great is the need for its transformation towards a circular economy in order to actually reduce emissions and care for the natural environment. Apart from further investments in renewable energy sources, the adaptation of conventional energy is also very important. At the moment, it is the basis of the Polish energy sector and it will probably not change for a long time. Despite the obvious disadvantages of using hard coal and lignite as energy fuel, a radical change in the system is not possible for economic and social reasons. In further parts of this work, the circular economy coefficients for the examples of various coal power plants were proposed and calculated to measure the transition of the energy sector from linear to circular economy.

D. Circular economy indicators- literature review

Monitoring the progress of the circular economy is a difficult task. The transition to a circular economy is not limited to specific materials or sectors. It is a systemic change that affects the entire economy and affects all products and services. There is no single widely recognized "circular indicator", and there is also a lack of ready-made, robust indicators describing the most important trends. It is not possible to adequately capture the complexity and multiple dimensions of the transition to a circular economy with a single measure or result. The adopted indicators are a derivative of the actions taken and the characteristics of the area of activity, therefore, when creating indicators for EU countries, it is important to review the available indicators on the basis of benchmarking and analysis of good practices.

Circular economy encourages the preservation of the value of products, materials and resources for as long as possible, returning them back to the production cycle at the end of their life and minimizing waste generation. Unlike previous industrial revolutions that focused on mass-producing goods, the current business sector transformation focuses on moving from selling goods to providing services. National, regional and local authorities should support the circular economy through sectoral policies as well as by creating funding platforms or systems.

In the Table 1 below, there are identified indicators enabling the assessment of progress in the transformation towards CE.

Table 1. Indicators enabling assessment of progress in the transformation towards CE.

Indicators enabling the assessment of progress in the transformation towards CE	Unit
Environmental indicators	
Direct resources consumption (DMI)	mln Mg
Resources consumption in enitre chain (RMC)	mln Mg
Resources consumption (TMC)	mln Mg
Switching from renewable fuels to renewable resources	%
Resource productivity (GDP/DMC)	$/mln Mg
Consumption of critical raw materials	mln Mg
Consumption of materials (DMC) per capita	mln Mg
Share of renewable energy in gross final energy consumption	%
Water consumption	mln m^3
Reuse of industrial water	%
Land use (direct)	% of arable land
Direct CO_2 emissions	mln Mg
Trace of CO_2 consumption	mln Mg
Energy efficiency	%

Total waste production	%
Production of municipal waste	%
Recycling of municipal waste	%
Recycling of total waste	%
Storage of waste	%
Environmental Performance Index (EPI)	%
Environmental Sustainability Index (ESI)	%
Greenhouse gases emissions	mln Mg of CO_2 eq.
Avoided wastes	%
Use of combustion by-products in various sectors of the economy	%
Amount of neutralized wastes	%
Amount of recycled wastes	%
Amount of hazardous wastes	%
Amount of non-hazardous wastes	%
Economic indicators	
The added value of the recycling industry	mln $
Environmental taxes	%
Value of purchase / sale of secondary raw materials	mln $
Economy (GDP)	mln $
Import of materials	mln $
Export of materials	mln $
The amount invested in circular economy projects	mln $
Share of the sector's capital expenditure	mln $
Social indicators	
Number of adopted directives / laws / regulations	-
Number of actions to raise public awareness	-
Average processing time for a by-product classification decision	days
Number of activities to promote a circular economy	-
Number of industrial and territorial ecology projects	mln $
Number of research projects in the field of circular economy	-
Number of scientists dealing with the topic of circular economy	-
Number of patents related to circular economy (recycling, eco-design)	-
Number and value of introduced eco-innovations	mln $
Number of renewable energy training courses	-
Green public procurement market volume	-
Number of small and medium-sized enterprises operating on the basis of circular economy	-
Number of products manufactured based on the circular economy concept	-
Companies that introduce innovations in accordance with circular economy	%
Number of Ecolabel certificates	-

Source: Kulczycka J., et al., 2019

The 51 indicators in above table contain 28 environmental indicators, 15 social and 8 economic indicators. They were chosen as an example of circular indicators base on Kulczycka et al., 2019, where there were analyzed 22 European countries and their approach to CE. The analysis was done based on different scales: for countries and for sample cities within them. In general, the indicators from the Table 1 above are not directly adjusted to one branch of industry or any specified scope. Indicators like for example Economy (GDP), Number of adopted directives/ laws/ regulations are intended of course to be applicable in bigger scale (countries) but mostly, they can be used in anywhere in the chain. As in this work, the energy sector is discussed many of environmental, economic, or social indicators from above can be adjusted to this on different levels. Total waste production, water consumption, direct CO_2 emissions and other. should be evaluated for countries' energy systems, enterprises or especially, what will be tried to evaluate in this work, in single power plants.

III. Circular Indicators in Power Sector

A. Critical analysis of indicators reported by companies

In the analysis there were 6 polish companies and 2 European ones taken under consideration. It was proceeded for generally 26 indicators (20 environmental, 4 economic and 2 social). For reports from 2019 and 2020, the frequency of indicators reporting was measured, and the results are presented in Table 2 below.

Table 2. Comparison of indicators reporting in 2019 and 2020

	2019	2020
Environmental indicators	69	90
Economic indicators	26	29
Social indicators	5	14
Total	100	133

Source: Own study

The collected data show that the selected indicators related to the circular economy, illustrating the activity of enterprises in the social, economic, and environmental areas in 2019, were collected in the number of 100. For 26 indicators and 8 companies included in the analysis, this gives an efficiency of 28%. In 2020, this efficiency increased to approximately 64%. If, on the other hand, one company was excluded, which significantly differs from the rest, the values would be 53% and 68% respectively.

B. Proposition of indicators for coal power plants

For the purposes of the circular economy, a list of recommended information for publishing has been compiled (Table 3). They can be further used to calculate proposed circular economy indicators for coal power plants (Table 4, next page). Some information would have the absolute values illustrating the scale of the problem. On the other hand, the indicators should be relative and related to the functional unit, which will allow for the direct comparison between individual entities.

Table 3. Data recommended to be reported to calculate CE indicators for coal power plants.

Data	Unit	Description
En	MWh	Total amount of energy produced, used in further indicators as a functional unit to obtain relative information about the company and easily obtain absolute data
P	MW	The installed capacity of power plants that can be used as another functional unit allows to obtain absolute values
F	kg or m^3	The total amount of fuel used to produce energy
LCC	kg or m^3	The amount of low calorific coal used in process of energy production with the description of LCC
Wa	kg	The amount of wastes generated
WaRC	kg	The amount of wastes that can be recycled
WaN	kg	The amount of wastes that can be neutralized
WaRCo	kg	The amount of wastes that can be recovered
CCPs	kg	The amount of coal combustion products generated during the process of energy generation, that are used as by-products further in the industry
W	m^3	The amount of water consumed
Ww	m^3	The amount of wastewater generated
NWw	m^3	The amount of neutralized wastewater
Fa	kg	The amount of fly ash produced in the process of generating energy
Em	eq kg CO_2	Sum of all emissions expressed as CO_2 equivalent emitted in the process of generating energy
*EmSO_2	kg SO_2	The amount of SO_2 emitted in the process of generating energy
*EmCO_2	kg CO_2	The amount of CO_2 emitted in the process of generating energy
*EmNO_x	kg NO_x	The amount of NO_x emitted in the process of generating energy
*EmCO	kg CO	The amount of CO emitted in the process of generating energy

Source: Own study

Some of the data in Table 3 are to serve as functional units (produced energy). They do not reflect the achievement of the objectives of the circular economy but will allow the conversion of other reported values into relative units that can be compared between different power plants of the same type.

The other recommended factors mainly concern the environment and the impact of power plants on it (water consumption, emitted greenhouse gases, waste management). Two things that may be characteristic of coal-fired power plants in this comparison are the LCC and CCPs factors, which are respectively: the amount of low-calorific coal burned by the power plant and the amount of coal combustion by-products used as a further product. At this point it should be noted that a given by-product must be approved for further use as a material, so the number of obtained permits and certificates for such products is also important.

C. *Measuring progress within one power plant*

Measuring the transformation towards a circular economy within a single power plant should be an essential task. It is the smallest link in the entire energy sector, so it should be the first focus. Only then can we try to compare power plants with each other and study the progress of the linear economy change on a larger scale.

To carry out an analysis on given indicators, first of all, one should start with collecting accurate data. When they are not widely reported, you can only try to draw conclusions, but they will not give the intended effect and the full picture of the situation. The comparison itself can be made on an annual basis, believing that each power plant would update the necessary data every year. An example where some information are available from previous years, as well as current data, is Belchatow power plant. On its website provides information on how much it managed to reduce certain emissions in the years in which the power plant operates (1989-2019). Although it is supported by charts, their scale does not allow for an accurate calculation of the change on an annual basis. They only give a picture of the entire activity and the approximate values in Table 5 show the reduction of fly ash, SO_2, NO_x the Belchatow power plant in 1989-2019.

Table 5. Data for calculation sample indicators

Year	Fly ash	SO_2	NO_x	Unit
2010	850	75000	42000	Mg
2011	830	78000	41000	Mg
2012	800	75000	40000	Mg
2013	750	60000	40000	Mg
2014	700	70000	37000	Mg
2015	800	75000	35000	Mg
2016	500	30000	29000	Mg
2017	600	40000	30000	Mg
2018	700	50000	32000	Mg
2019	700	30000	25000	Mg

Source: Belchatow Power Plant official website

Looking at the above table, it is easy to notice a positive trend in reducing emissions of all three mentioned emissions. The power plant is successively investing in modernization and improvement of exhaust gas cleaning systems, and it is giving very good results. Both the use of modern electrostatic precipitators for the removal of fly ash and the construction of new flue gas desulphurization installations based on the use of the wet lime-gypsum method to reduce sulfur dioxide resulted in over 90% reduction of these emissions.

Table 4. Recommended indicators for coal power plants

Indicator	Unit	Description	Equation	Equation No.
LCC%	%	Share of low calofiric coal in total amount of used fuel	$LCC\% = \frac{LCC}{F}$	1
EnLCC	%	Share of energy produced from LCC in total amount of energy produced	$EnLCC = \frac{CV_{LCC} * eff_{pwoer\ plant}}{En}$	2
IWa	kg/FU (or multiples)	Amount of wastes generated per functional unit	$I_{Wa} = \frac{Wa}{En}$	3
Wa%	%	Percentage share of various waste management methods (reuse, recycling, neutralization, recovery, etc.) in relation to the total waste generated	$Wa_{RC}\% = \frac{Wa_{RC}}{Wa}$ $Wa_{N}\% = \frac{Wa_{N}}{Wa}$ $Wa_{RCo}\% = \frac{Wa_{RCo}}{Wa}$	4
IW	l/FU (or multiples)	Water consumption per functional unit	$I_W = \frac{W}{En}$	5
IWw	l/FU (or multiples)	Amount of wastewater generated per functional unit	$I_{Ww} = \frac{Ww}{En}$	6
NWw%	%	Share of neutralized sewage	$NWw\% = \frac{NWw}{Ww}$	7
CCPs%	%	The share of CCPs that are used as secondary raw materials in the total amount of wastes generated	$CCPs\% = \frac{CCPs}{Wa}$	8
Ifa	kg/ FU	The amount of fly ash produced in the process of generating energy per functional unit	$I_{Fa} = \frac{Fa}{En}$	9
IEm	eq kg CO_2/ FU (or multiples)	Sum of all emissions expressed as CO_2 equivalent generated in the process of generating energy per functionall unit	$I_{Em} = \frac{Em}{En}$	10
*IEmSO$_2$	kg SO_2/ FU (or multiples)	The amount of SO_2 generated in the process of generating energy per functional unit	$I_{EmSO2} = \frac{EmSO2}{En}$	11
*IEmCO$_2$	kg CO_2/ FU (or multiples)	The amount of CO_2 generated in the process of generating energy per functional unit	$I_{EmCO2} = \frac{EmCO2}{En}$	12
*IEmNO$_x$	kg Nox/ FU (or multiples)	The amount of NO_x generated in the process of generating energy per functional unit	$I_{EmNOx} = \frac{EmNOx}{En}$	13
*IEmCO	kg CO (or multiples)	The amount of CO generated in the process of generating energy	$I_{EmCO} = \frac{EmCO}{En}$	14
Eff	%	Efficiency of power plant	This indicator should be reported directly	15

Source: Own study

Moreover, several modernizations and investments have been made to optimize the combustion process and thus a 55% decrease in NO_x emissions over the last 30 years has been achieved. Based on the found information, it is difficult to talk about specific values but presented approximation is enough to notice the positive change taking place in the power plant. Over time, probably, it was not dictated by the will to transform towards a circular economy, but by other regulations that affect the change of the linear economy.

D. *Measuring progress among different power plants*

The methodology of the simplified analysis itself consists in comparing the values of indicators for power plants of the same type, showing which of them best fits into the canons of the circular economy. An additional indicator in the full analysis could be the amount of reported data, based on which the indicators recommended for monitoring the transformation towards a circular economy can be calculated. This would not provide information strictly about the transformation itself, but it showed the power plant's approach to reporting itself, and thus cooperation in meeting the assumptions of the circular economy.

IV. RESULTS AND DISCUSSION

A. *Analysisof results for Belchatow Power Plant*

Based on Table 5 for Belchatow Power Plant and using formulas 9, 12 and 13, calculation for I_{Fa}, I_{EmSO2}, I_{EmNOx} was made. In this example last 10 years was taken under consideration and the results are presented in the Table 6. For the calculations, as a functional unit was taken the energy generated in 2019, if within last 10 years the amount of electricity produced was on the same level.

Table 6. Results of calculation of sample indicators.

Year	Calculated indicators			Unit
	I_{Fa}	I_{EmSO2}	I_{EmNOx}	
2010	26.2	2307.7	1292.3	kg/ MWh
2011	25.5	2400.0	1261.5	kg/ MWh
2012	24.6	2307.7	1230.8	kg/ MWh
2013	23.1	1846.2	1230.8	kg/ MWh
2014	21.5	2153.8	1138.5	kg/ MWh
2015	24.6	2307.7	1076.9	kg/ MWh
2016	15.4	923.1	892.3	kg/ MWh
2017	18.5	1230.8	923.1	kg/ MWh
2018	21.5	1538.5	984.6	kg/ MWh
2019	21.5	923.1	769.2	kg/ MWh

Source: Own study

After the calculation of values for sample indicators, the next step to proceed with the analysis is to compare them between each other to see the difference and the change that can be measured from one year to another. In Table 7 below, this change is presented. The values were calculated using the equation:

$$Change = \frac{V_{year}}{V_{year-1}} - 1 \tag{15}$$

where:

V_{year} is the value of an indicator in following year,

V_{year-1} is the value of an indicator in a previous year.

Table 7. Change of the indicators among the years.

Year	Indicators		
	I_{Fa}	I_{EmSO2}	I_{EmNOx}
2011	-2%	4%	-2%
2012	-4%	-4%	-2%
2013	-6%	-20%	0%
2014	-7%	17%	-7%
2015	14%	7%	-5%
2016	-38%	-60%	-17%
2017	20%	33%	3%
2018	17%	25%	7%
2019	0%	-40%	-22%

Source: Own study

Additionally, the change over whole decade was calculated. The rule was the same as in equation 15 just the values of indicators were taken from years 2019 and 2010 and they are -18%, -60% and -40% for fly ash indicator, SO_2 indicator and NO_x indicator, respectively.

Moreover, one of the proposed indicators are tracked from 1989 by Belchatow Power Plant itself and the results are presented in the Figure 3. Power plant presents accumulated data for the reduction of CO_2 emissions per MWh, which stays for I_{EmCO2} proposed.

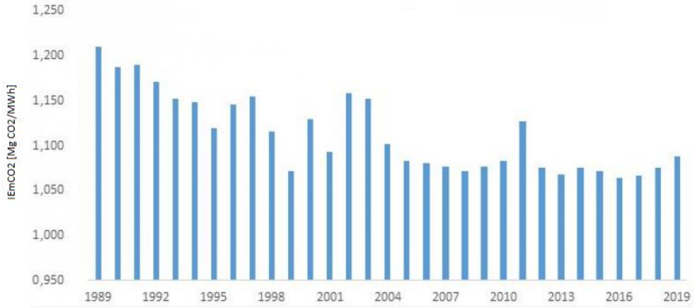

Figure 3.CO_2 emissions indicator for Belchatow Power Plant between 1989 and 2019

Source: Belchatow Power Plant official website

From the Tables 6,7 and Figure 3, it can be noticed that general trend with decreasing amount of these greenhouse gases produced it is a goal of Belchatow power plant. Looking at last 10 years in case of CO_2 emission indicator there is no huge progress towards decreasing its amount produced yearly. There are some slight fluctuations, even with an increase in last three years. It is not comforting but might be a sign that the time for next modernization or some repairs, to keep the trend, has come.

Three calculated indicators present the same trend as CO_2 and fluctuates over last 10 year, but here the change over the decade is very huge and satisfactory. The power plant was able to reduce all three greenhouse gases emissions by even 60%, which is very good. Probably, as in case with earlier describe data, the changes have been pushed by law, environmental policies and limits other than circular economy approach. Nevertheless, the positive change has appeared and influences CE as well.

When analyzing the obtained results for sample coefficients, it should be remembered that they represent only a small part of the entire activity of the power plant. They are focused on emissions of harmful gases, which covers only a part of the environmental area of the proposed indicators. When talking about a circular economy, we must think about all its aspects, including social and economic aspects. Based on the calculated indicators, it can be assumed that the Belchatow Power Plant is going in the right direction and the transformation towards CE. However, given such limited data, it cannot be clearly stated and classified as a part of the circular economy assumptions.

B. Analysis of results of comparizone of different power plants

Based on the proposed indicators for power plants operating on hard coal or lignite Table 4, formulas 1-13 and the real data found on official websites of sample power plants, calculations were made. Their results are presented in Table 8.

Table 8. Results of calculations of proposed indicators for coal power plants.

Indicator	Power Plant					Unit
	Belchatow	Kozienice	Rybnik	Turow	Drax	
IWa	N/A	N/A	1275	947	N/A	kg/MWh
IW	N/A	N/A	N/A	N/A	11.8	mln m^3/MWh
IWw	N/A	N/A	N/A	204	N/A	mln m^3/MWh
CCPs%	N/A	N/A	86%	100%	N/A	%
Ifa	0.022	0.022	0.038	0.019	0.300	kg/MWh
IEm	N/A	N/A	N/A	N/A	158.6	Mg eq CO_2/MWh
IEmSO_2	0.92	0.68	0.42	0.17	0.11	kg SO_2/MWh
IEmCO_2	1.08	0.88	N/A	0.42	130.60	Mg CO_2/MWh
IEmNO_x	0.77	0.70	N/A	0.29	0.52	kg NO_x/MWh
IEmCO	0.65	N/A	N/A	0.022	N/A	kg CO/MWh
Eff	39% (42%)	38% (45%)	-	NA (42%)	-	%

Source: Own study

The table above clearly shows that most of the recommended indicators have not been calculated. Due to the lack of data needed to perform the calculations, it was not possible. As with official sources, emission factors were mainly calculated. Only two of the proposed indicators were possible to calculate for all four example power plants. When it comes to waste indicators and how to deal with them, there are clear gaps in the reported information, and hence in the calculation of the indicators. Only for two power plants it was possible to calculate the use of coal combustion by-products. Also, the emissions themselves could not be approached in a way that generalizes them to the CO_2 equivalent and gives a comprehensive picture of the effects of electricity production. The data about the efficiency in the parenthesis is a sing that nowadays, power plants investing in the newest and most advanced technologies. Unfortunately, the majority of blocks were built even 40 years ago, and they required modifications.

The results show that the Turow Power Plant, which is the smallest in terms of installed capacity and burns lignite, has the best indicator results. As the only one of the analyzed power plants, it also provides information on the generated wastewater and uses 100% of coal combustion by-products further in industry. This is very important due to the circular economy and allows us to assume that among the power plants included in the study, the transformation in question is the best. An additional difficulty in such an analysis is the lack of defined boundaries of the linear economy and the circular economy, and the lack of a clear definition of the latter. This makes it impossible to make a clear thesis that a given power plant unambiguously meets or does not meet its assumptions. This is undoubtedly a field for experts to standardize the definitions so that it is possible to present clear conclusions.

C. Discussion

The purpose of this work was to propose indicators to measure the transformation towards a circular economy from the current linear economy system. At a time when many materials can be found that approach the transformation in the macro or meso scales, indicators for the micro scale of the energy industry, i.e., power plants, were recommended in this work.

Some of the proposed indicators are more general and can be applied to different types of industry and on a different scale (such as I_W, which informs about the amount of water used by a power plant / company / energy system), while some are specific to one type of power plant, such as such as CCPs (amount of coal combustion products that can only be used in coal-fired power plants). After a preliminary analysis of the energy industry, it was noticed that they publish a lot of information that may have an impact on the discussed transformation and present its real picture. On this basis, several indicators for coal power plants were proposed. An attempt was made to calculate them and check the transformation within one power plant on Belchatow Power Plant example, followed by a comparison among the available power plants. The Belchatow example shows that the change that takes place in it may be the beginning of a transformation towards a circular economy, but the information obtained does not allow to clearly state whether the power plant follows the concept of a circular economy. The analyzed data for the last 10 years show significant fluctuations that may result from the adoption of an inadequate amount of energy as a functional unit affecting the results or from third factors, such as e.g., temporary shutdown of one block from use, ongoing modernization or simply a change in the produced energy corresponding to the requirements system. If, on the other hand, this analysis is carried out in a wider time window (10 years instead of 1 year), a significant improvement can be seen in 3 out of 4 analyzed indicators, which may mean that the transformation is slow and is not necessarily dictated by the circular economy trend, but a positive effect dressed up by others transformation.

As for the recommended indicators themselves, their limitations are reduced to the type of power plant. They can be used both in Poland and other countries. The conducted analysis would not work in the case of other types of power plants, such as photovoltaic power plants, wind farms or eco-incineration plants, the operation characteristics of which are different, and the emissions, pollutants, methods of dealing with them or top-laid requirements are various. Under ideal conditions, having a complete set of data to carry out a detailed analysis, knowing the boundaries, using the recommended indicators, you can decide whether the activity of power plant is linear or circular.

The presented analysis can be considered preliminary and giving a picture of the general problem. The first step in further research in this direction should be to clearly define the boundaries of the circular economy. At the same time, the method of reporting data by energy producing units should be standardized, so that on their basis it is possible to calculate a greater number of coefficients, the same for different power plants and possible to compare with each other. The greater the number of calculated indicators, the more precisely one can try to determine the course of transformation of a given unit. Provided that data from previous years were also available.

V. Conclusions

The circular economy is a tool that should significantly affect the development of energy sectors. The biological cycle of the circular economy is related to the management of, inter alia, biomass, the potential of which is not fully used in many countries, including Poland. Current use of biomass does not fully meet CE assumptions. It should be kept in circulation if possible and used in a cascade. The increasing amount of waste, which can serve energy purposes, EU directives and laws, and opportunities to improve the economy, make the circular economy an inevitable future. As CE is an element necessary to achieve the objectives European Green Deal, failure to implement its assumptions and requirements may not only reduce the quality of life of citizens, but also financial penalties for countries that fail to comply with it. An important point has legal situation. In Poland has changed a lot in recent years and reflects an attempt to adapt to the guidelines of the circular economy. A challenge that will be faced in the coming years will be the restructuring of the energy sector towards low-emission energy. It is a field of innovative investments currently being slowly implemented by companies from the energy sector. Noteworthy ideas should also include decentralization, dispersion of generation sources and the development of energy recovery from municipal waste, the potential of which is very large and may be of great importance for the circular economy and the entire national power system. The designed solutions and technological innovations favorably influencing the development of circular economy should consider the specificity of the sector at the design stage and try to ensure the stable operation of the system as much as possible, guaranteeing security. In the whole system, many changes are still needed, technology development, awareness, and further investments, but looking at the current trends, one can be positive, believing that we are on the right track to transform a linear economy into a circular economy, and thus protect the natural environment against negative influence of the current economic system.

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