TÉCNICO LISBOA

Circular economy indicators in power sector

Przemyslaw Jan Dygas

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Manuel Guilherme Caras Altas Duarte Pinheiro

Prof. Magdalena Bogacka

Examination Committe

Chairperson: Prof. Jorge de Saldanha Gonçalves Matos

Supervisor: Prof. Manuel Guilherme Caras Altas Duarte Pinheiro

Member of the Committee: Prof. Tânia Alexandra dos Santos Costa e Sousa

January 2021

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the *Universidade de Lisboa*.

Abstract

The process of transformation of a linear economy into a circular economy requires monitoring and supervision of progress. At present, in the literature, you can find many examples of indicators that can be used for this purpose, but they are not strictly focused on studying this transformation in the energy industry, therefore in this work, based on the literature review, 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 analyze the transformation inside the example power plants: Belchatow Power Plant and the British Drax Power Stations, and to compare the transformation process between different coal-fired power plants. Due to the availability of materials, it was done not using the main proposed method, but a simplified method. The analysis shows that a positive change has been taking place in the energy sector for years, but it is impossible 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 it is 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, DEA method, Polish energy sector, circular economy factors, monitoring of the circular economy.

Resumo

O processo de transformação de uma economia linear em uma economia circular requer monitoramento e supervisão do progresso. Atualmente, na literatura, é possível encontrar muitos exemplos de indicadores que podem ser utilizados para esse fim, mas eles não estão estritamente focados no estudo dessa transformação na indústria de energia, portanto neste trabalho, com base na revisão da literatura, indicadores de a economia circular foram propostas, por exemplo, tipos de usinas baseadas no sistema de energia polonês e suas necessidades. Também foi feita uma tentativa de analisar a transformação dentro das unidades energeticas: Belchatow Power Stations (Polónia) e as British Drax Power Stations (Reino Unido), e para comparar o processo de transformação entre diferentes instalações energéticas movidas a carvão. Devido à disponibilidade de materiais, não foi feito o método principal proposto, mas sim um método simplificado. A análise mostra que há anos ocorre uma mudança positiva no setor de energia, mas não é possível afirmar com clareza se uma determinada usina funciona de acordo com os conceitos de economia circular. Em muitos aspetos, faltam dados específicos compartilhados, e os coeficientes para os quais é possível não fornecem uma imagem completa da situação. Por isso, na discussão que sintetiza todo o trabalho, foram recomendados novos passos e medidas necessárias para acompanhar de maneira eficaz a transformação para uma economia circular.

Palavras chave:

economia circular, setor de energia, método DEA, setor de energia Polaco, fatores de economia circular, monitorização

Table of contents

List of figures

List of tables:

List of figures:

List of symbols

BG1 - amount of biofuels of 1 generation used t produce energy,

BG1% -biofuel generation 1 indicator, share of BG1 in F,

BG2 - amount of biofuels of 2 generation used t produce energy,

BG2% - biofuel generation 2 indicator, share of BG2 in F,

BG3 - amount of biofuels of 3 generation used t produce energy,

BG3% - biofuel generation 3 indicator, share of BG3 in F,

Bp - amount of by-products,

Bp% - by-products indicator, share of Bp in Wa,

CCPs - amount of coal combustion products,

CCPs% - coal combustion products indicator, share of CCPs in Wa,

Em -emissions expressed as emitted CO_2 equivalent,

EMo - exhausted modules,

$EmSO_2$ - amount of SO_2 emissions,

$EmCO_2$ - amount of CO_2 emissions,

$EmNO_x$ - amount of NO_x emissions,

EmCO - amount of CO emissions,

En - total amount of energy produced,

EnLCC - LCC energy indicator, share of energy produced from LCC in total amount of energy produced,

F - amount of fuel,

Fa - amount of fly ash produced,

I_{Fa} - fly ash indicator, amount of fly ash generated per functional unit,

I_{Em} - emissions indicator, emissions expressed as equivalent of CO_2 per functional unit,

I_{EmSO2} -SO_2 indicator, SO_2 emissions per functional unit,

I_{EmCO2} - CO_2 indicator, CO_2 emissions per functional unit,

I_{EmNOx} - NO_x indicator, NO_x emissions per functional unit,

I_{EmCO} - CO indicator, CO emissions per functional unit,

I_W - water indicator, water consumption per functional unit,

I_{Wa} - wastes indicator, wastes per functional unit,

I_{Ww} - wastewater indicator, wastewater generation per functional unit,

LCC - amount of low calorific coal used,

LCC% - LCC indicator, share of LCC in F,

MT - photovoltaic module's type,

NWw - amount of neutralized wastewater,

NWw% - neutralized wastewater indicator, share of neutralized wastewater,

P - power plant's installed capacity,

REM - amount of exhausted modules that are recycled,

REM% - share of REM in EM,

Rf - amount of biomass used to produce energy,

Rf% - biomass fuel indicator, share of Rf in F,

W- amount of water consumed,

Wa - amount of generated wastes,

WaN - amount of wastes that can be neutralized,

Wa_N% - WaN indicator,share of WaN in total amount of wastes,

WaRC - amount of wastes that can be recycled,

Wa_{RC}% - WaRC indicator,share of WaRC in total amount of wastes,

WaRCo - amount of wastes that can be recovered,

Wa_{RCo}% - WaRCo indicator,share of WaRCo in total amount of wastes,

Ww - amount of wastewater generated,

1. Introduction

1.1 Need of appropriate information

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 other 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 is 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 could 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).

1.2 Goal and scope

The aim of this thesis is to identify, analyze and propose circular economy indicators for power sector that could support the transformation towards a circular economy begin 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, and for comparison, a foreign power plant was used.

1.3 Methodology

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

1. First, preparing the theoretical background about work issues, circular economy itself, already defined circular economy indicators and Polish energy market 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, biomass power plants and photovoltaic 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 DEA method to evaluate the progress toward circular economy based on proposed indicators between different power plants and simplified method for current conditions,
5. Calculation of recommended indicators for sample power plants and applying methods from point 3 and 4,
6. Discussion the results and further recommendations.

1.4 Thesis structure

The work below has been divided into 5 chapters. The first one, which corresponds to the first chapter, is an introduction that fulfills the task of defining the problem and defining the goal and scope, the methodology followed, and presenting the work structure.

The second chapter is a theoretical chapter. First, it characterizes the circular economy, and then presents information about the Polish energy system, which served as the basis for further analysis. It is an example for which the indicators proposed and developed in the following section are of the greatest importance due to its characteristics and the significant advantage of coal in electricity production. The following section reviews the literature on the circular economy and the indicators that can be used to measure the transformation from a linear economy to a circular economy.

Chapter 3 contains an analysis of the meso scale of the Polish energy system with a list of indicators and information reported by the largest companies in this industry and a proposal of indicators that can monitor the progress of transformation towards a circular economy for three types of power plants: coal power plants, biomass power plants and photovoltaic power plants. Later in this chapter, we propose ways to use the recommended indicators to analyze individual power plants and their internal changes, and to compare the changes that occur between different units.

Chapter 4 is devoted to an attempt to apply these indicators in exemplary power plants and to discuss the results of this analysis. To check the progress towards a circular economy inside one power plant, the example of the Belchatow Power Plant and the foreign example - Drax Power Station were used for comparison. All the work was completed with a discussion and conclusions (chapter 5).

2. State of knowledge

2.1 Circular economy

Circular economy (CE) 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.*, 2016).

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).

Simplified idea of circular economy is presented in the Figure 1 below.

Figure 1. Simplfied idea of circular economy

Source: Sphera website

2.2 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 have to 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).

Although renewable energy is considered clean, it is important to remember about the entire life cycle of materials such as batteries or photovoltaic panels. They are built of rare earth metals, the resources of which are also dwindling. In addition, both solar and wind farms need large spaces, and biomass production is associated with a huge demand for good soil and freshwater resources. Moreover, the number and efficiency of RES installations depends on a given region in Poland. Some places have great potential for wind energy, while others have good sun exposure, which increases the profitability of solar power plants. Regardless of what is used to produce energy, everything must be properly disposed of at the end of its service life.

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 in Poland is based mainly on the combustion of hard coal and lignite. During combustion, harmful gases and 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 a number of 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 CCPs (coal combustion by-products) 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)

2.3 Composition of energy sector

The Polish energy system is based mainly on hard coal and lignite, which accounted for 50.4% (23.9 GW) and 19.6% (9.3 GW) of installed capacity in Poland in 2019, respectively. Thus, keeping at around 70%. Renewable energy sources also have a significant impact on the Polish energy sector, which together account for 20.1% (9.5 GW). However, they are divided into different sources, the main ones being onshore wind farms 12.5% (5.9 GW) of the total and photovoltaic plants 3.2% (1.5 GW), followed by hydro, biomass and biogas plants (Macuk R., 2020). Total installed capacity in Poland in 2019, divided by sources, is shown in the Figure 2 below.

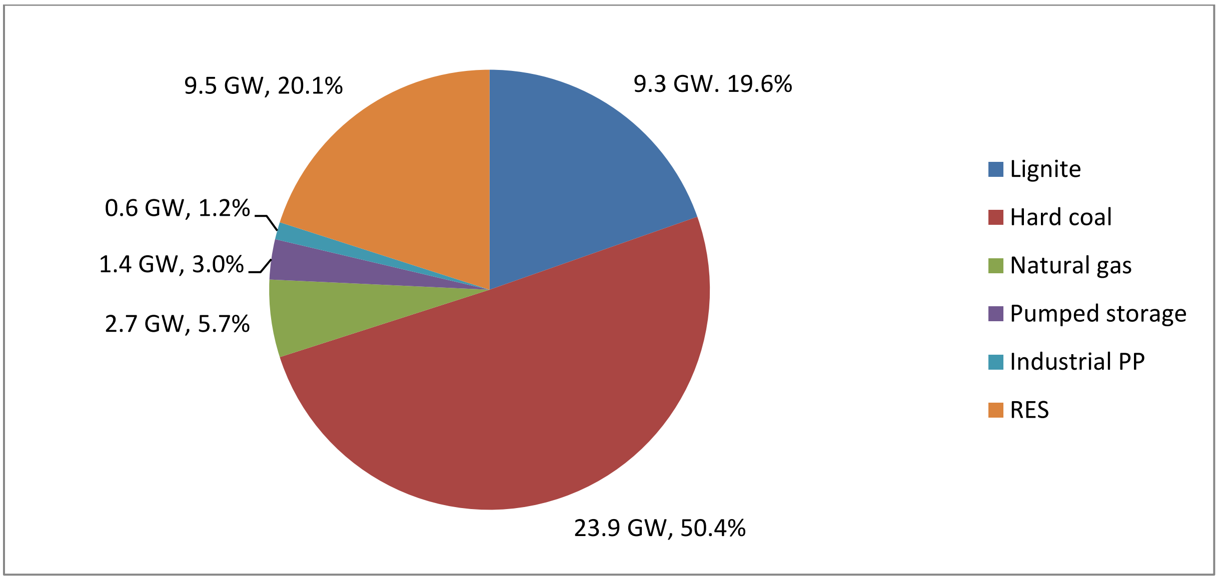

Figure 2. Total installed capacity in Poland in 2019
Source: Macuk R., 2020

When it comes to electricity production, of course, hard coal ranks first with 78.9 TWh of energy produced (48.1%), followed by lignite with 41.7 TWh of energy produced (25.5%) and renewable energy sources with 25.2 TWh (15.4%). The undisputed leader among them is onshore wind farms, producing 15.1 TWh (9.2%) (Macuk R., 2020). The rest of them produce rather trace amounts of energy. Natural gas is also an important fuel, from which Poland obtains 14.5 TWh (8.8%) of electricity. Total produced energy in Poland in 2019, divided by sources is presented in the Figure 3 below.

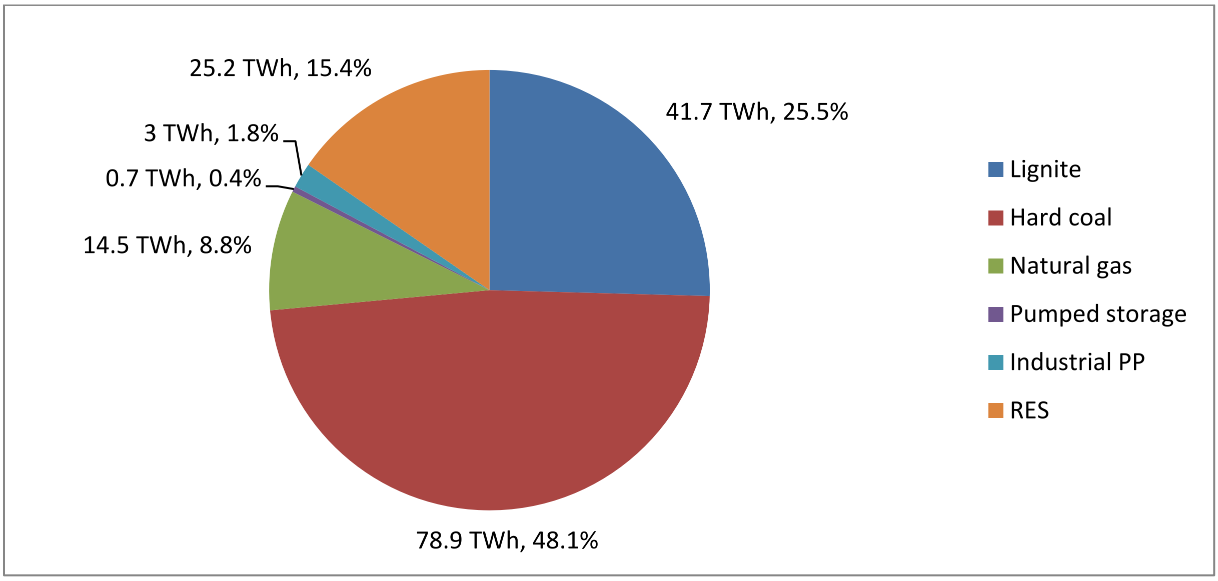

Figure 3. Total energy production in Poland in 2019
Source: Macuk R., 2020

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 in power plants based on hard coal, natural gas and a significant increase in the area of 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 4 below.

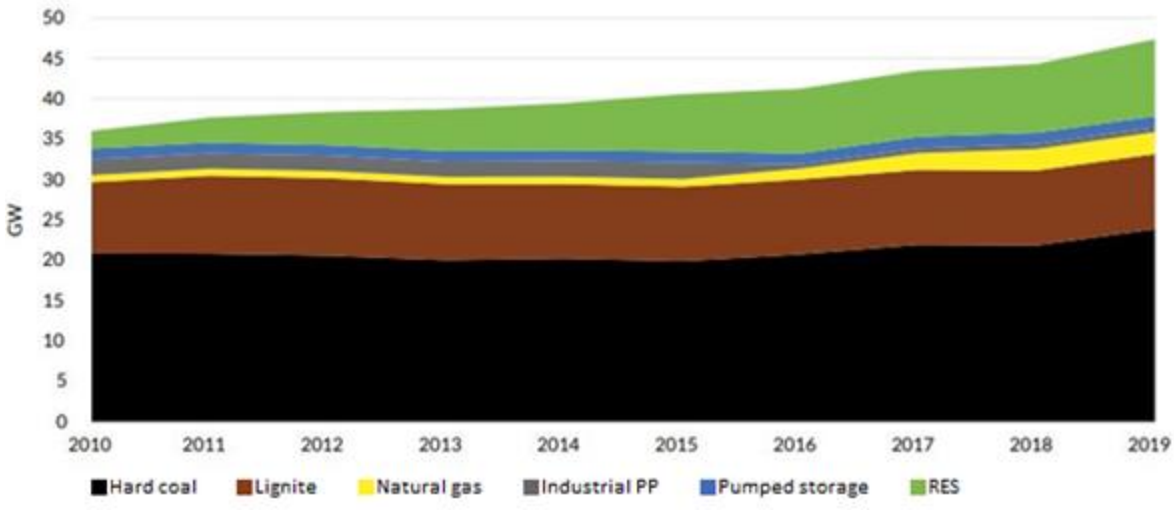

Figure 4. Change of installed capacity in Poland between 2010 and 2019
Source: Macuk R., 2020

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 2010 and 2019 is shown in Figure 5 below.

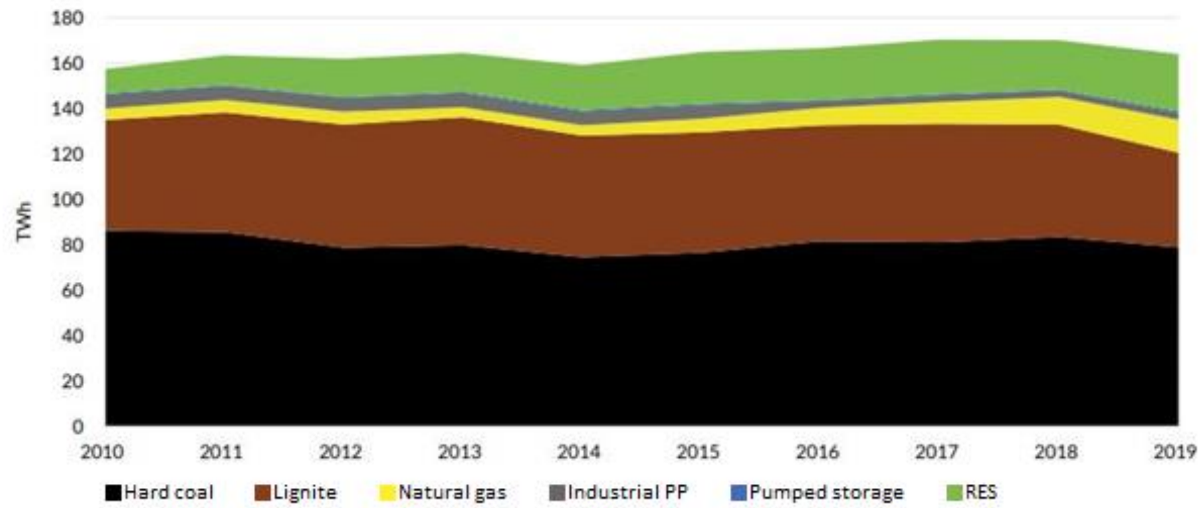

Figure 5. Change of total electricity production in Poland between 2010 and 2019
Source: Macuk R., 2020

In renewable energy sources alone, the last decade can be divided into two stages. The first one in 2010-2016, which was led by a sharp increase in capacity in onshore wind farms and a smaller but also significant increase in biomass plants. In 2016, there was a breakthrough and investments in photovoltaics began. The development of other types of power plants ceased in favor of the development of solar energy. Mainly small, home installations. From 2010 to 2019, about 7.5 GW of installed capacity increased, reaching the level of 9.5 GW in 2019. The change of installed capacity in RES between 2010 and 2019 in Poland is presented in Figure 6 below.

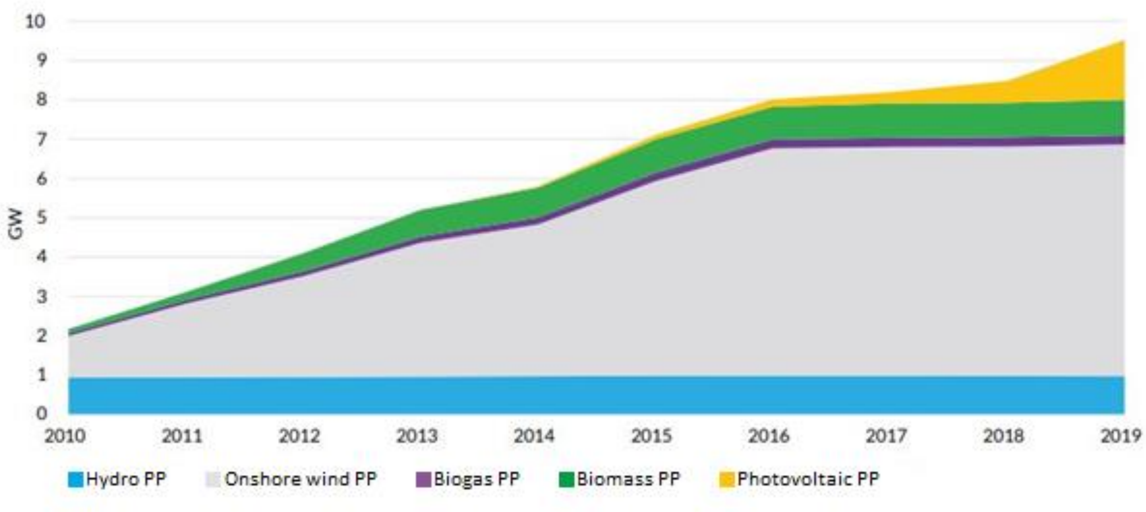

Figure 6. Change of installed capacity in RES in Polans between 2019 and 2019
Source: Macuk R., 2020

Electricity production from renewable energy sources has been quite complex over the past 10 years. In 2010, the production of about 11 TWh of electricity was equally divided between hydro, biomass, onshore wind and conventional with biomass co-firing (with a slight predominance of this source). In 2019, the situation changed dramatically. Co-firing of biomass has depreciated, and biomass power plants have gained. Onshore wind farms producing 15.1 TWh out of 25.2 TWh in total produced by RES were the decisive number. The change of electricity production from RES in Poland between 2010 and 2019 is presented in Figure 7 below.

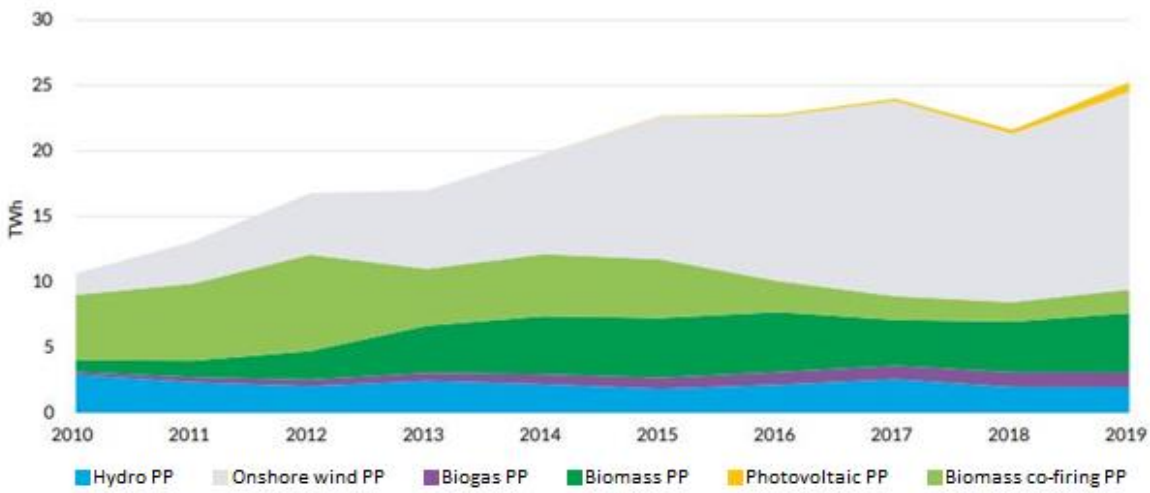

Figure 7. Change of electricity production from RES in Poland between 2010 and 2019
Source: Macuk R., 2020

As for greenhouse gas emissions, 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 tonnes 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 to 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. Now, 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 later chapters of this work, the circular economy coefficients for the examples of various power plants were proposed and calculated to measure the transition of the energy sector from linear to circular economy.

2.4 Circular economy indicators

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 based on 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 EASAC report there is a set of environmental indicators advocated by different programs, initiatives, or organizations. Firs set of sustainable development indicators that can be used for evaluation of sustainable development goals and tracking transformation towards circular economy is created by United Nations Environment Programme (UNEP) and was created in accordance to major global problems, such as: natural resource use (air, land, water, biodiversity), climate change or chemicals and wastes. The United Nations Development Programme (UNDP) developed 17 Sustainable Development Goals, which are focused on ending poverty, fighting with inequality and injustice and tackle climate change. Next comprehensive set of indicators was advocated by Global Reporting Initiative (GRI) and contains sustainability-relevant indicators for organisations. These include indicators connected to energy, materials, water, wastes and recycling as environmental indicators, but also other related to economy and social aspects. Yale and Columbia Universities together with the World Economic Forum has developed next set of indicators. Environmental Sustainability Index (ESI) and Environmental Performance Indicator (EPI) rank countries performance in protection of human health from environmental harm and protection of ecosystems.

The World Bank has assembled 50 indicators called Little Green Data Book to measure the progress on the sustainable development goals (SDGs) and emphasize trends in the environment. Green Growth Indicators is next set that was developed by the OECD and contains 25-30 indicators divided in four groups:

1. Environmental and resource productivity (carbon and energy productivity, resource productivity, water productivity and multifactor productivity).
2. Natural asset base (natural resource stocks, renewable stocks, non-renewable stocks, biodiversity, and ecosystems).
3. Environmental dimension of quality of life (environmental health risks, services, and amenities).
4. Economic opportunities and policy responses (technology and innovation, environmental goods and services, financial flows, training and skills development, regulations and management approaches, prices, and transfers).

Some of mentioned indicators are relevant to CE but there is more exact information obtained in economy-wide material flow accounts (EW-MFA). They are extensively used to measure efficiency of trends in resources' area and were developed by Eurostat together with the Wuppertal Institute. Ellen MacArthur foundation (EMF) has the vision of circular economy indicators based on existing meters:

1. Resource productivity measured as gross domestic product (GDP) per Mg of direct resource

consumption (DMI). Although the data is easily available, the result is not related directly to environmental impact.

2. Circular activities. It is very problematic to find suitable data so recycling rate and eco-innovations indexes may be used instead.
3. Waste generation presented as municipal waste generated per capita and wastes generated per GDP.
4. Energy and green house gases emissions illustrated by greenhouse gases emissions per GDP and renewable energy use.

The EU Resource Efficiency Scoreboard (EURES) and Raw Material Consumption (RMC) base on the most recent statistics to present development in resource productivity. The purpose is to apply indicators presenting progress in a resource-efficient economy. It is supposed to contain indicators covering resource use in whole production chain to join measures to ensure reduction of the environmental impacts of production and consumption, taking under consideration differences in economics of different countries.

The European Innovation Partnership (EIP) also implemented plan for ensuring sustainable supply of non-energy, non-agricultural raw materials to the European economy. The plan covers activities in areas of improving technology, non-technology initiatives (improving waste management framework and good practice) and includes tracking the progress by proper indicators based on Raw Material Scoreboard, that was published with 24 indicators from below areas:

- raw materials,
- circular economy and recycling,
- competitiveness and innovation,
- social and environmental sustainability,
- framework conditions for mining.

The set of the above-mentioned indicators is presented in Table 1 and 2 below.

Table 1. Indicators included in EASAC report.

Indicator ser	Advocated by	Characteristic/ data source	Number of indicators
Sustainable Development Indicators	UNEP	Major global environmental issues	10
Sustainable Development Goals	UNDP	End poverty, fight inequality and injustice, and climate change	17
Corporate sustainability	Global reporting initiative (GRI)	Sustainability-relevant indicators for organizations	>100
Environmental sustainability index (ESI); environmental performance indicator (EPI)	Yale and Columbia universities	Environmental indicators	21 (ESI) 20 (EPI)

Source: EASAC, 2016

Table 2. Indicators included in EASAC report

Indicator ser	Advocated by	Characteristic/ data source	Number of indicators
Little Green Data Book	World Bank	Environmental and sustainability	50
Green Growth Indicators	OECD	Environment, resource, economic and policy responses	25-30
Economy-wide material flow accounts EW-MFA	Eurostat Wuppertal Institute	Focused on material flows	6
Circular economy indicators	Ellen MacArthur foundation (EMF)	Indicators currently available	7
Resource efficiency	EU Resource Efficiency scoreboards (EURES)	Eurostat, EEA and others	32
Raw materials	European Innovation Partnership (EIP)	Raw Materials Scoreboard European Union Raw Materials Knowledge Base (EURMKB)	24 4

Source: EASAC, 2016

The circular economy is a cross-sectoral concept, so it is necessary to cover a wider spectrum of thematic categories, including economic growth, materials management, waste, people's quality of life. Monitoring indicators should consider aspects such as economic, environmental, and social so indicators presented below are divide, respectively.

In the Tables 3,4 and 5 below, there are identified indicators enabling the assessment of progress in the transformation towards CE.

Table 3. Indicators enabling the 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)	M Mg
Resources consumption in enitre chain (RMC)	M Mg
Resources consumption (TMC)	M Mg
Switching from renewable fuels to renewable resources	%
Resource productivity (GDP/DMC)	$/M Mg
Consumption of critical raw materials	M Mg
Consumption of materials (DMC) per capita	M Mg
Share of renewable energy in gross final energy consumption	%
Water consumption	M m^3
Reuse of industrial water	%
Land use (direct)	% of arable land
Direct CO_2 emissions	M Mg
Trace of CO_2 consumption	M Mg
Energy efficiency	%
Total waste production	%

Source: Kulczycka et al., 2019

Table 4. Indicators enabling the assessment of progress in the transformation towards CE

Indicators enabling the assessment of progress in the transformation towards CE	Unit
Environmental indicators	
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	M 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	%
Ratio of total energy production to global energy consumption	%
Economic indicators	
Employment growth	% of total employment
The added value of the recycling industry	M $
Resource self-sufficiency	Kg extraction/ kg DMI
Environmental taxes	%
Value of purchase / sale of secondary raw materials	M $
Economy (GDP)	M $
Import of materials	M $
Export of materials	M $
The amount invested in circular economy projects	M $
Share of the sector's capital expenditure	M $
Level of recycling and preparation for re-use of paper, metals, plastic and glass from municipal waste	%
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	M $
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	M $
Number of EMAS certificates introduced	-
Number of renewable energy training courses	-

Source: Kulczycka et al., 2019

Table 5. Indicators enabling the assessment of progress in the transformation towards CE.

Indicators enabling the assessment of progress in the transformation towards CE	Unit
Social indicators	
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 et al., 2019

The 56 indicators in above table contain 29 environmental indicators, 16 social and 11 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 tables 2 and 3 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 at al. should be evaluated for countries' energy systems, enterprises or especially, what will be tried to evaluate in this work, in single power plants.

Circular Economy is an approach to promote the responsible and cyclical use of resources. In recent years, CE has been endorsed as a policy to minimise burdens to the environment and stimulate the economy. Diverse nations are adopting CE around the world. Macro-scale circular economy monitoring currently mainly includes methods that use material flow analysis (MFA) and input-output analysis (Kalmykova et al.,2018). In the literature, you can find an overview of the tools and methodologies that are used.

The authors showed that none of the indicators and methodologies could monitor all features. Most of the indicators focus on recycling strategies. This is a consequence of the fact that for years there has been a lot of attention to recycling, which is now also one of the most used concepts / strategies in the circular economy. Although the European Commission proposed a monitoring framework for CE and organizations like Ellen MacArthur Foundation are working on formulation on in, there is no one widely agreed concept of CE. There are different interpretations of what CE should present and where is the border to cross to work along with CE idea (Moraga et al., 2019).

Due to the ambiguous definition of the circular economy, it is also difficult to define what and how should be monitored. Depending on the adopted CE limits, the same examined indicators may lead to different conclusions. Based on the literature review, it can be noticed that various authors made attempts to analyze the tools and methodologies used so far Elia et al. (2016) based on the CE characteristics from the European Environment Agency, she has shown that there is no single indicator that monitors all the characteristics (Elia et al., 2016).

On the other hand, Lacovidou et al. (2017). Has shown that none of the methods of assessing the recovery of resources from waste alone is sufficient to cover different dimensions (environmental, economic, social, and technical) (Lacovidou et al., 2017).

2.5 Strategies

The way to classify the indicators with boundary marks covering the different approaches to the circular economy is to distinguish between two CE definitions: *sensu strictu* and *sensu latu*. The first of them is characterized by CE with two features: slowing down and closing the loop of natural resources. The slowdown is influenced by the extended period of use, extended service life through modernization and repair. Closing the loop is nothing more than the circulation of resources in the loop and their reuse as secondary material. *Sensu latu* definition focuses more on a social and economic approach in which important decisions are already made in the planning, design and management phases. (Moraga et al., 2019)

There are different scales to implement the circular economy. The basic division is based on micro, meso and macro scales. In any case, this terminology is not followed and consistently applied (Kirchherr et al., 2017). For a clear definition, in addition to defining the scale itself, it is useful to define a specific scope of the analysis. In the case of the energy industry, one may incline to the statement that individual power plants or local energy companies fit into the micro scale. The meso scale may be national energy systems or corporations covering the areas of one or several countries. The macro scale, on the other hand, may extend beyond the borders of the country or even the continent, having a global overtone.

Moraga et al. (2017) in their work proposed six strategies to measure the implementation of CE. Each of the strategies focuses on different aspect. Strategy 1 preserve the function of products and services by circular business models, Strategy 2 based on increasing lifetime of product by improving its durability and activities like remanufacturing, reusing etc. Strategy 3 preserves component of products in a way of repurposing or recovery. Strategy 4 says recycling of materials, Strategy 5 is about using embodied energy by energy recovery and Strategy 6, which considers a reference scenario measurement. To show the progress (or regress) towards circular economy by comparing the effect after implementation of Strategies 1-5 with the status, when linear economy is implemented. The Strategies 1-6 are presented in Table 6 and 7 below.

Table 6. Proposed strategies for circular economy indicators

Strategy	Description
Strategy 1	Preserve the function of products or services provided by circular business models such as sharing platforms, PPS (use- and result- oriented), and schemes promoting product redundancy and multifunctionality.
Strategy 2	Preserve the product itself through lifetime increase with strategies such as durability, reuse, restore, refurbish, and remanufacture.
Strategy 3	Preserve the product's components through the reuse, recover and repurposing of parts.

Source: Moraga et al., 2019

Table 7. Proposed strategies for circular economy indicators.

Strategy	Description
Strategy 4	Preserve the materials through recycling and downcycling
Strategy 5	Preserve the embodied energy through energy recovery at incineration facilities and landfills.
Strategy 6	Measure the linear economy as the reference scenario or the absence of a preservation strategy to show the status, progress, or regress towards CE. For example, the indicator for waste generation per person in a year might show whether the promotion of CE is generating less waste.

Source: Moraga et al., 2019

Additionally, to strategies described above, the evaluation of the circularity may be based on the indicators that are direct or indirect, as the circularity may have direct and indirect influence on the economy (Potting et al., 2018). Due to the lack of the clarity thinking about the definition of CE it is not clear what these direct and indirect means. Combining this with definitions *sensu stricte* and *sensu latu* make available to keep both measurements in the classification framework, so the indicators can be divided accordingly.

1. Direct Indicator with Specific Strategies. The strategies that the indicator focuses on can be identified.
2. Direct Indicator with Non-specific Strategies. One strategy that the indicator focuses on cannot be easily identified. It can focus on more than one strategy (Geng et al., 2012).
3. Indirect Indicator. The indicator that is not directly connected with CE definition (Moraga et al., 2019).

3. Circular indicators in power sector- own study

3.1 Critical Analysis of indicators of reporting company

To identify indicators of the circular economy in the energy industry, official reports of companies concerning their sustainable development, activities within the framework of Corporate Social Responsibility (CSR), social and integrated reports were analyzed.

Based on the previously prepared group of 26 indicators influencing the circular economy, divided into three areas: environmental, economic, and social (20 environmental indicators, 4 economic indicators, 2 social indicators), it was checked whether the given companies report relevant data.

The 2019 data analysis results were then compared with the 2020 results to compare the reporting progress of the companies. The results of both analyzes are presented in Tables 8,9 and 10 and discussed.

Table 8. Indicators reported in companies' reports in 2018.

Indicator	Company name and indicator's occurance								
	Energa	PGE	Enea	Veolia Poland	Tauron	Polenergia	E.ON	Enel	Frequency of occurrence of individual indicators
Environmental indicators									
Overall installed capacity	-	+	-	-	+	+	-	+	4
Installed capacity in RES	-	+	-	-	+	+	-	+	4
Overall energy produced	+	+	+	-	+	+	-	+	6
Energy produced from RES	-	+	+	-	+	+	+	+	6
Amount of on-renewable resources used	+	-	+	-	+	-	-	+	4
Amount of renewable resources used	+	-	-	-	+	-	-	+	3
Energy consumption	-	-	+	-	+	-	-	+	3
Direct emissions	+	+	+	-	+	+	-	+	6
Indirect emissions	+	-	-	-	-	-	-	+	2
Emissions according to production	-	+	-	-	-	-	-	+	2
Emissions reduction	-	-	-	+	-	-	-	-	1
Amount of hazardous waste	+	-	+	-	+	-	+	+	5
The way of dealing with hazardous waste	+	-	-	-	+	-	+	+	4
Amount of non-hazardous waste	+	-	+	-	+	-	+	+	5
The way of dealing with non-hazardous waste	+	-	-	-	+	-	+	+	4

Source: (Dygas i Generowicz, 2020)

Table 9. Indicators reported in companies' reports in 2018.

Indicator	Company name and indicator's occurance								
	Energa	PGE	Enea	Veolia Poland	Tauron	Polenergia	E.ON	Enel	Frequency of occurrence of individual indicators
Environmental indicators									
Amount of by-products	+	-	-	-	-	-	-	-	1
Reuse of by-products	-	-	-	-	+	-	-	-	1
Water consumption	+	-	+	-	-	-	+	+	4
Water consumption according to production	-	-	-	-	-	-	-	+	1
Amount of wastewater	+	+	-	-	-	-	-	+	3
Economic indicators									
Investments in environmental protection	+	+	+	+	+	-	+	+	7
Investments in modernization	+	+	+	-	+	-	+	+	6
Investments in environmental projects	+	+	+	+	+	-	+	+	7
Investments in RES	+	+	+	-	+	-	+	+	6
Social indicators									
Trainings for employees	+	-	-	-	-	-	-	+	2
Social initiatives	+	-	-	-	-	-	+	+	3

Source: (Dygas i Generowicz, 2020)

Based on the analysis of six Polish companies from the energy industry, including Energa, PGE, Enea, Veolia Polska, Tauron and Polenergia, the presentation of their activities in various types of reports (social reports, integrated reports, CSR reports) was already in 2019 is a common practice, which is partly due to the obligation introduced by legal provisions (e.g., CSR reports for large business entities).

They include descriptions of activities aimed at environmental protection, several investments in renewable energy sources and modernization processes that improve the quality of energy production and transmission processes, along with limiting their negative impact on the environment and increasing energy efficiency. The information needed to monitor the transformation towards circular economy in the field of environmental indicators is also discussed in detail (data on waste, emissions, share of renewable energy sources, raw materials, water and sewage). The situation is similar in the case of financial data and new investments. Reported social data focuses both on the structure within the organization and external activities in the sphere of sport, culture, and education, as well as on cooperation with the society in order to increase energy awareness and depart from the linear model of the economy.

The analysis of foreign companies from the energy industry shows that the creation of integrated reports on its activities was a common practice. Two exemplary companies, E. ON and Enel, were included in the analysis. In one of them, the information presented is very detailed in the field of environmental, economic, and social activities. The reports contain information on waste, emissions, the share of renewable energy sources, raw materials, water and sewage in the environmental area, new investments, implementation of pro-ecological projects, activities for environmental protection and modernization, as well as economic and social cooperation with consumers.

Table 10.Indicators reported in companies' reports in 2019.

Indicator	Company name and indicator's occurance								Frequency of occurrence of individual indicators
	Energa	PGE	Enea	Veolia Poland	Tauron	Polenergia	E.ON	Enel	
Environmental indicators									
Overall installed capacity	+	+	-	-	+	+	-	+	5
Installed capacity in RES	+	+	-	-	+	+	-	+	5
Overall energy produced	+	+	+	+	+	+	-	+	7
Energy produced from RES	+	+	+	-	+	+	+	+	6
Amount of on-renewable resources used	-	-	+	-	+	+	-	+	4
Amount of renewable resources used	+	-	+	-	+	-	-	+	4
Energy consumption	+	-	+	-	+	-	+	+	5
Direct emissions	+	+	+	+	+	-	+	+	7
Indirect emissions	+	-		-	-	+	+	+	4
Emissions according to production	-	+	-	-	-	-	-	+	2
Emissions reduction	+	-	+	+	+	+	+	-	6
Amount of hazardous waste	+	-	+	-	+	-	+	+	5
The way of dealing with hazardous waste	+	-	-	-	+	-	+	+	4
Amount of non-hazardous waste	+	-	+	-	+	-	+	+	5
The way of dealing with non-hazardous waste	+	-	-	-	+	-	+	+	4
Amount of by-products	+	-	-	-	+	-	-	-	2
Reuse of by-products	-	+	+	-	+	-	-	-	3
Water consumption	+	+	+	-	+	+	+	+	7
Water consumption according to production	-	-	-	-	-	-	-	+	1
Amount of wastewater	+	+	-	-	+	-	-	+	4
Economic indicators									
Investments in environmental protection	+	+	+	+	+	-	+	+	7
Investments in modernization	+	+	+	+	+	-	+	+	7
Investments in environmental projects	+	+	+	+	+	+	+	+	8
Investments in RES	+	+	+	-	+	+	+	+	7
Social indicators									
Trainings for employees	+	-	+	+	+	+	-	+	6
Social initiatives	+	+	+	+	+	+	+	+	8

Source: Own study based on official companies' reports

With reference to the analysis in the article (Dygas and Generowicz, 2020) for the 2019 reports, the same analysis was carried out based on the current data from 2020 for a comparative purpose. The same companies from the energy sector, both from Poland, were considered and Europe and the same group of indicators. As in the previous edition, also now, companies willingly reported any activities for environmental protection, pro-ecological investments, and modernizations. While the reporting of economic data related mainly to energy and environmental projects has remained at a comparable, high level, considering the environmental indicators, progress can be seen both among domestic and foreign companies. More often you can find information on important topics directly related to the circular economy and "closing the loop", such as: the amount of by-products generated by a company in its activities and information on the management of these products.

There is also a significant difference when it comes to the company's energy consumption. Among the selected environmental indicators, the greatest progress in reporting is visible in the harmful emissions reduction indicator. There is the biggest difference among social indicators. The two indicators included, in 2019, were reported five times in total, mainly by foreign companies and one Polish company. In 2020, they were reported fourteen times, i.e., almost three times more often. It should be noted, however, that this group is not wholly and directly related to the circular economy. As in the previous year, in addition to promoting the circular economy model, energy awareness of environmental protection, companies report their external activities in the sphere of sport and culture.
Often, there is also no information about the measurable effects and efficiency of the actions taken, and there is only general information about given activities. The collective results of the above analyzes are presented in Table 11 below.

Table 11. 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 studies.

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 48%. In 2020, this efficiency increased to approximately 64%. If, on the other hand, one company was excluded, which significantly differs from the rest in terms of the reported indicators, the values would be 53% and 68%, respectively.

3.2 Proposal of circular indicators for different types of power plants

The implementation of the circular economy concept requires the development of evaluation methods for the process of its implementation in enterprises. It is especially important because enterprises are the basic area of its implementation. The problem is the application of CE targets, which are not clearly defined globally to a more specific level, such as power plants in this case. This is mainly due to the global shaping of CE targets related to the entire life cycle of materials or services and the lack of a specific definition of the circular economy. It is impossible to fully define the conditions, the fulfillment of which would mean the achievement of CE by an individual power plant. The production of CE indicators is more partial throughout the chain. On the other hand, directions can be indicated in which the power plants should go, and the assessment itself may be based on the comparison of the power plant operations with each other. It is a simplified approach to the transformation towards a circular economy but can provide a lot of useful information.

The process of constructing CE meters must begin with constructing the conditions necessary to achieve it. If they will cover priority directions from the global level, they can include:

1. minimization of the negative impact on the environment,
2. minimizing the use of resources,
3. improving energy efficiency,
4. running a business in the long term.

A comprehensive measure that allows for the assessment of the advancement of the transformation towards CE should consider all the above-mentioned conditions, and it may be management efficiency as is the case with constructing measures of sustainable development (Adamczyk & Nitkiewicz, 2008). It is a very broad criterion that allows to include economic, technical, ecological, and social aspects, and its essence boils down to achieving the goals, maintaining the correct relationship between the effects and the expenditure needed to achieve them.

The 4 aspects mentioned above are presented in the Table 9 below. Some of them can be considered important depending on the specific type of power plant. However, it is not possible to favor one aspect over another due to the limited access to information. The proposed indicators in sections 3.2.1., 3.2.2, 3.2.3 are intended to standardize the reported data to apply them to the overall analysis of power plants and to compare them with each other.

Table 12. Four aspects of CE and their goals

Aspect	Goal
Environmental	Rational use of natural resources, minimizing the generation of waste and pollution in the energy production process while maximizing their reuse. Limiting the negative impact on the environment.
Economic	Minimization of costs and expenses while maximizing benefits and effects
Social	Using human potential, contributing to the improvement of living conditions and enabling development
Technological	Optimization of production processes, increasing the efficiency of production processes, ensuring an efficient technical and technological infrastructure

Source: Adamczyk and Nitkiewicz, 2008

It is also important to find the links between the various aspects. This is necessary to assess the transformation towards CE.

In the previous paragraph, the Polish energy system was described since it will be tried to conduct the analysis below mainly based on it. Considering its characteristics, the dominant types of power plants are those powered by hard coal and lignite; therefore, they will be the main point of the analysis. The analyzed types of power plants will be characterized in chapters 3.2.1, 3.2.2 and 3.2.3. These will be coal-fired, biomass-enriched power plants and photovoltaic power plants. In addition, currently published reports and official information will be analyzed to identify indicators reported so far and new indicators will be proposed for all the above-mentioned types of power plants.

3.2.1 Coal power plants

As it was presented in paragraph 2 of this work, polish energy sector is mostly based on burning coal. For the Polish economy, for political and geographical reasons, it is the most profitable means of obtaining energy. On the other hand, unfortunately, it is the most harmful to the environment. Despite the advancing technology, improving the efficiency of power plants and reducing the pollutants that they generate, their harmful effects remain undisputed. With reference to the circular economy, it is also difficult to imagine coal-fired power plants that fit into its canons. It is impossible to recycle burnt coal. However, as you know, you must look at the entire life cycle of coal. From its extraction, through its use to its disposal.

At the mining stage, you can follow the idea of "the mining circular economy", which has evolved from circular economy practices. Its theory is to use resources rationally, reduce pollution, recycle more mining waste, and dispose of residues in an environmentally friendly manner. There are three main currents in the use of coal today.

The first one assumes electricity as an intermediary in the development of industries with high energy consumption. The next one is the direct conversion of coal through the processes of coking, gasification, liquefaction and use in the chemical industry. The third one is the development and use of hard coal-related minerals. (Zhen Wei et al., 2020) However, this is more important in assessing the mine's transformation towards a circular economy. For power plants, you need to focus more on the use of coal and the management of its residues. About 700 million tonnes of anthropogenic materials are produced in Europe each year. They contain about 150 million tons of CCPs of which Poland alone produces over 20 million tons (Rosiek, 2018).

These products can be widely used in many industries. Fly and liquid ash in construction for concrete mixtures, construction binders or as an additive to construction ceramics. In the mining industry for sealing and insulating fire fields. In road construction to stabilize the terrain and maintain good condition of roads in the winter season. They can also be used for the disposal of acidic industrial wastewater and municipal wastewater. Their use in agriculture is also popular to improve calcium fertilizers and soil deacidification. Increasing the use of CCPs contributes to meeting the objectives of the circular economy and minimizes energy demand and the generation of greenhouse gases. It has been shown that one ton of coal combustion by-products used in place of cement or lime reduces greenhouse gas emissions by 50 tons (Chrzanowski & Masłowski, 2014).

The predictions about the production and use of coal combustion by-products are shown in Table 13 below.

Table 13. Predictions about the production and use of coal combustion by-products.

Characteristic	Year				
	2015	2016	2017	2018	2019
Generation of CCPs (total, thousand Mg)	21110	21210	22120	22450	23440
Using of CCPs (total, thousand Mg), including:	12109	11935	11828	11792	11701
Ratio (in %): Using of CCP (total, thousand Mg/ Generation of CCP (total, thousand Mg)	57.36	56.27	23.47	52.52	49.91
Production of clinker	1130	1141	1153	1164	1176
Cement production	1581	1597	1589	1621	1637
Concrete production	1038	1049	1070	1091	1102
Ceramics	700	707	721	736	743
Binders and plasters	1650	1667	1683	1700	1700
Coal mining	2000	1980	1921	1863	1807
Macrolevellings	2400	2160	2052	1990	1931
Road construction	1500	1485	1440	1397	1355
Other uses	110	150	200	230	250
For landfill disposal	8996	9275	10292	10659	11740

Source: (Chrzanowski & Masłowski, 2014)

When analyzing the above table, you can clearly see a downward trend. Every year, more CCPs are produced, while their use remains at the same level, which means that the share of coal combustion products used in total decreases. Maximizing the use of CCPs is a must when it comes to transforming conventional energy towards a circular economy. In Poland, it is particularly important due to the dominant position of coal. Numerous studies have shown coal combustion products to be useful as a valuable economic, environmental, and social resource (Rosiek, 2018).

As for the middle stage, i.e., the use of coal after its extraction, Polish power plants also have a lot of catching up to do towards the circular economy. The Dirty 30 report shows that among the 30 European thermal power plants that emit the most carbon dioxide annually, there are as many as 4 Polish power plants. The first place in the entire ranking is the Belchatow power plant with a capacity of 5298 MWe and an annual production of 27.18 CO_2, 16th place is the Kozienice power plant with a capacity of 2840 MWe and 10.23 CO_2 production per year, 19th place is the Turow power plant with a capacity of 1505 MWe and an annual production of 9.99 CO_2. and on site 25 Rybnik power plant with a capacity of 1720 MWe and production of 8.39 CO_2 per year.

Poland is therefore the third country in Europe in this respect (after Great Britain and Germany) (Europe's Dirty 30, 2014). This clearly indicates the need to modernize and invest in modern flue gas cleaning technologies to reduce greenhouse gases produced. This applies to Poland as well as other countries based on hard coal and lignite.

To diagnose the current progress towards a circular economy, the presently reported environmental, social and economic indicators for exemplary coal-fired power plants were analyzed in the further part of the work. On their basis, new indicators were proposed and, later in the work, methods of their evaluation.

Based on the official information published by the power plants, their compilation was made. As in the case of companies in the energy sector, efforts were made to specify environmental, financial, and social data that could affect the circular economy. The power plants listed above were considered (Belchatow, Kozienice, Rybnik and Turow). The results are shown in Table 14 below.

Table 14. Data and indicators reported by sample power plants in 2019.

Data	Power plant name and indicator's occurrence					Frequency of occurrence of individual indicators
	Belchatow	Kozienice	Rybnik	Turow	Drax	
Environmental indicators						
Type of fuel	+	+	+	+	+	5
Installed capacity	+	+	+	+	+	5
Energy produced	+	+	+	+	+	5
CCPs	+	+	+	+	-	4
Reuse of CCPs	+	-	-	+	-	2
Emission of fly ash	+	+	-	+	+	4
Reduction of emission of fly ash	+	+	-	-	-	2
SO_2 emissions	+	+	+	+	+	5
Reduction of SO_2 emissions	+	+	-	-	-	2
CO_2 emissions	+	+	-	+	+	4
Reduction of CO_2 emissions	+	+	-	-	-	2
NO_x emissions	+	+	+	+	+	5
Reduction of NO_x emission	+	+	-	-	-	2
Water consumption	-	-	-	+	+	2
Amount of waste water	-	-	-	+	-	1
CO emissions	+	-	-	+	-	2

Source: Own study

As can be seen from the table above, individual data reporting by power plants is practiced, but not to the same extent as it is the case for entire companies in the energy sector. On the official sites of included power plants, you can find data mainly on environmental indicators. In addition to basic information such as the power of a given power plant and the amount of energy produced, data on emissions of individual greenhouse gases and coal combustion products are most often provided.

From the examples given, power plants often provide general data, e.g., when referring to the use of combustion by-products, it is only mentioned, not supported by specific data. When it comes to environmental and social indicators, power plants often refer to the performance of entire companies in which they are, again referring to general activities rather than specific data-supported activities. The activities and plans presented by the power plants show their awareness of the need to implement new solutions in line with the environment and the good of civilization. In terms of the transformation towards a circular economy, they are a good start, but not sufficient to illustrate and oversee this transformation.

For the purposes of the circular economy, a list of recommended information for publishing has been compiled (Table 15). They can be further used to calculate proposed circular economy indicators for coal power plants (Table 16 and 17). 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 15. Data that is recommended for reporting to calculate circular economy indicators for coal power plants

Data	Unit	Description
En	MJ or MWh (or multiples)	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 (or multiples)	The installed capacity of power plants that can be used as another functional unit allows to obtain absolute values
F	kg or m^3 (or multiples)	The total amount of fuel used to produce energy
LCC	kg or m^3 (or multiples)	The amount of low calorific coal used in process of energy production with the description of LCC
Wa	kg (or multiples)	The amount of wastes generated
WaRC	kg (or multiples)	The amount of wastes that can be recycled
WaN	kg (or multiples)	The amount of wastes that can be neutralized
WaRCo	kg (or multiples)	The amount of wastes that can be recovered
CCPs	kg (or multiples)	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 (or multiples)	The amount of fly ash produced in the process of generating energy
Em	eq kg CO_2 (or multiples)	Sum of all emissions expressed as CO_2 equivalent emitted in the process of generating energy
*$EmSO_2$	kg SO_2 (or multiples)	The amount of SO_2 emitted in the process of generating energy
*$EmCO_2$	kg CO_2 (or multiples)	The amount of CO_2 emitted in the process of generating energy
*$EmNO_x$	kg NO_x (or multiples)	The amount of NO_x emitted in the process of generating energy
*EmCO	kg CO (or multiples)	The amount of CO emitted in the process of generating energy

Source: Own study

* alternative for general emissions *Em*

Some of the data in Table15 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.

Table 16. 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

Source: Own study

Table 17. Recommended indicators for coal power plants

Indicator	Unit	Description	Equation	Equation No.
$*IEmSO_2$	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 functiona 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

* alternative for general emissions *Em*

3.2.2 Biomass power plants

Biomass is the biodegradable fraction of products, waste or residues of biological origin from agriculture (including plant and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste (European Parliament and Council Directives 2009/28 / EC of 23 April 2009 on the promotion of the use of energy from renewable sources, amending and subsequently repealing Directives 2001/77 / EC and 2003/30 / EC). For energy purposes, mainly such biomass as wood, straw and other agricultural waste, energy crops, organic and municipal waste, animal excrement, organic waste as well as vegetable oils and animal fats are used.

Biomass is a product of the photosynthesis reaction, so its production in the natural environment may be spontaneous. This makes it the least capital-intensive renewable energy source. Its basic ingredients are carbohydrates, starch, and lignin. The first two, as they are food for humans and animals, are the target product of agricultural crops. Moreover, they are the raw material needed to produce ethanol. The remaining parts are energy raw materials and depend on the type of plant. Carbon dioxide emitted during the energetic use of biomass is used in its creation. It can be said that in the world of plants it completes the cycle and, being the end of the chain, it is also its beginning.

In Poland, in 2018 electricity was produced from this fuel: 5.3 TWh (24.7% of all electricity produced in Poland from renewable energy sources), heat - 13.4 PJ (90.5%), and the maximum capacity of power plants using biomass as fuel was 735 MW (8.8 %) (Bernet-Kowalska et al., 2018). The largest of them is the Połaniec power plant with a designed capacity of 205 MW (the results of biogas are not included in the data provided). It is assumed that the calorific value of biomass as an energy carrier is half that of coal and amounts to about 10-15 MJ / kg (Lewandowski, 2007).

The biomass itself can be used in many ways. The simplest of them is direct combustion in appropriate boilers (straw, wood, pellets), co-combustion with other energy carriers (coal, fuel oil) or its further processing. Direct combustion of biomass is best from an environmental point of view as it has a very low ash and sulfur content. On the other hand, it has a low calorific value, so it is often used to "refine" coal, which has worse environmental parameters but a higher calorific value. Co-firing reduces the sulfur concentration and lowers the costs of flue gas desulfurization. Other possibilities of using biomass are its incomplete combustion and its fermentation, resulting in biogas (bacterial fermentation) or methanol, ethanol, and other compounds (aerobic fermentation) (Lewandowski, 2007).

Advantages of using biomass for energy purposes:

- domestic supplies of the energy carrier,
- taking advantage of food overproduction,
- reduction of carbon dioxide emissions, which, unlike non-renewable fuels for biomass, is balanced with its use for its production,
- reduction of desulfurization costs when co-incinerating with coal.

Disadvantages of using biomass for energy purposes:

- NO_x formation in decentralized energy production units is more expensive than in large power plants,
- in the case of biomass contaminated with pesticides, plastic waste or chlorinated compounds, substances with a toxic and carcinogenic effect are released,
- for some types of biomass, the removal of molten ash from the grate can be problematic (Lewandowski, 2007).

Biomass has been described because it fits with the concept of a circular economy, and power plants operating on this fuel are considered ecological. However, to accurately determine whether a given power plant meets the assumptions of a circular economy with its operations, it is necessary to monitor its work on issues important for a given type of economy. In this case, as in the case of other power plants and entire companies, environmental, social, and economic indicators are the main determinants.

When analyzing Polish power plants operating on biomass, it can be noted that these are small units mainly using co-firing with coal. For this reason, there is no reported data specifically for this type of fuel, even though the characteristics of these fuels are different, just as the information reported for them should be different. Table 18 below shows the information recommended for biomass power plants to be reported for further calculations of proposed circular economy indicators for biomass power plants, that are presented in Table 19.

Table 18. Data that is recommended for reporting to calculate circular economy indicators for biomass power plants.

Data	Unit	Description
En	MJ lub MWh (or multiples)	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 (or multiples)	The installed capacity of power plants that can be used as another functional unit allows to obtain absolute values
F	kg or m^3 (or multiples)	The total amount of fuel used to produce energy
*Rf	kg lub m^3 (or multiples)	The amount of biomas used to produce energy
BG1	kg lub m3 (or multiples)	The amount of biofuel of first generation used for production energy
BG2	kg lub m3 (or multiples)	The amount of biofuel of second generation used for production energy
BG3	kg lub m3 (or multiples)	The amount of biofuel of third generation used for production energy
Wa	kg (or multiples)	The amount of wastes generated
WaRC	kg (or multiples)	The amount of wastes that can be recycled
WaN	kg (or multiples)	The amount of wastes that can be neutralized
WaRCo	kg (or multiples)	The amount of wastes that can be recovered
Bp	kg (or multiples)	The amount of wastes that can be reused (by-products)
W	m^3	The amount of water consumed
Ww	m^3	The amount of wastewater generated
NWw	m^3	The amount of neutralized wastewater
Em	eq kg CO_2 (or multiples)	Sum of all emissions expressed as CO_2 equivalent emitted in the process of generating energy
Em	eq kg CO_2 (or multiples)	Sum of all emissions expressed as CO_2 equivalent emitted in the process of generating energy
Fa	kg	The amount of fly ash produced in the process of generating energy
**$EmSO_2$	kg SO_2 (or multiples)	The amount of SO_2 emitted in the process of generating energy
**$EmCO_2$	kg CO_2 (or multiples)	The amount of CO_2 emitted in the process of generating energy
**$EmNO_x$	kg NO_x (or multiples)	The amount of NO_x emitted in the process of generating energy
**EmCO	kg CO (or multiples)	The amount of CO emitted in the process of generating energy

Source: Own study

* only for power plants combining biomass with conventional fuel

** alternative to general emissions *Em*

Table 19. Recommended indicators for biomass power plants

Indicator	Unit	Description	Equation	Equation No.
Eff	%	Efficiency of power plant	This indicator should be reported directly	15
**Rf%	%	The share of Rf in total amount of fuel	$Rf\% = \frac{Rf}{F}$	16
BG1%	%	The share of BG1 in total amount of fuel	$BG1\% = \frac{BG1}{F}$	17
BG2%	%	The share of BG2 in total amount of fuel	$BG2\% = \frac{BG2}{F}$	18
BG3%	%	The share of BG3 in total amount of fuel	$BG3\% = \frac{BG3}{F}$	19
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, broken down into hazardous and non-hazardous waste.	$Wa_{RC}\% = \frac{Wa_{RC}}{Wa}$ $Wa_{N}\% = \frac{Wa_{N}}{Wa}$ $Wa_{RCo}\% = \frac{Wa_{RCo}}{Wa}$	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
Bp%	%	The share of Bp that are used as secondary materials in the total amount of wastes generated	$Bp\% = \frac{Bp}{Wa}$	20
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 functiona 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

Source: Own study

* only for power plants combining biomass with conventional fuel.

** alternative to general emissions *Em*

As can be seen in the table above, a large part of it covers the indicators proposed for conventional power plants. This is due to the general goals set for the energy sector aimed at combating emissions and minimizing the negative impact on the natural environment. Characteristic indicators for biomass should be the definition of the type of biomass used in the process. Depending on the generation, and thus - origin, it may fit into the canons of the circular economy. It is undeniable, however, that all biomass as fuel should be developed.

3.2.3 Photovoltaic power plant

Solar energy is classified as a renewable energy source. Obtaining energy from the sun is a known and common form of obtaining energy. Only part of the radiation of the appropriate wavelength reaches the Earth's surface. Due to this parameter, radiation can be divided into ultraviolet. It accounts for only 0.4% of solar radiation and is harmful to humans and animals, causing sunburn. As high-energy radiation, it is in the band between 10 and 400nm. Visible radiation accounts for about 44% of solar radiation and it enables vision to appear as light. It is in the band from 400nm to 750nm. Infrared radiation, responsible for the perception of heat, constitutes the largest part of solar radiation - 52%. It is invisible to humans, and its wavelength is over 1000 nm (Hodana et al., 2012).

The light beam coming from the atmosphere undergoes physical reactions such as reflection (17% is reflected by clouds, 6% from the Earth's surface), refraction (8%) and absorption (20% absorbed by the atmosphere, 4% by clouds), which means that only 45% reaches Earth. Due to the nature of the radiation, we can distinguish:

- direct radiation - a type of radiation characterized by short waves. It extends in a straight line from the sun and accounts for about 35-55% (depending on the season and weather conditions),
- diffuse (diffusion) radiation - radiation characterized by long waves, resulting from refraction, reflection, or partial absorption of direct radiation. Depending on the weather conditions, it is around 55% in the summer months, and around 70% in the winter months,
- radiation reflected from the earth's surface (albedo) - the ratio of the radiation reflected from the Earth's surface to the total radiation coming from the sun. The average albedo for our planet is 0.3. The highest is for areas covered with fresh snow - 0.8.

There are many ways to use the same solar radiation. With the help of photovoltaic cells, they can be converted directly into electricity. Individual cells are combined into groups to form photovoltaic panels, which are available in many types. All of them are mostly made of silicon and we distinguish between:

- monocrystalline cells - made of one silicon crystal which gives an efficiency of about 20%,
- polycrystalline cells - made of crystallized silicon. It has an efficiency lower than a

monocrystalline cell, about 14-18%, but it is also cheaper,

- amorphous cells - made of non-crystallized silicon and has a low efficiency of 6-10%, which makes it the cheapest of the mentioned types of cells.

Mono and polycrystalline cells are classified as 1st generation cells. They currently dominate the photovoltaic market, thanks to the fact that they have the best value for money. Amorphous cells and those produced from other elements such as CdTe (tellurium and cadmium) and CIGS (copper, indium, gallium, and selenium) are classified as second-generation cells. Due to the thin-film nature of the active semiconductor, the process of their creation is easier and less energy-consuming than the 1st generation. However, they are used less frequently due to their low efficiency. Perovskite and third generation cells are also becoming alternatives to previous generations. However, they require further improvements in terms of their low efficiency.

Electricity can also be obtained indirectly from thermal energy. This can be done with the help of so-called solar towers. The air heated by solar radiation is lifted upwards, which drives the windmills in the tower. They generate electricity by doing the work and driving the turbine. In this way, solar energy is first converted into heat energy and then into electricity (Hodana et al., 2012).

Advantages of solar radiation energy:

- omnipresence, the ability to install virtually anywhere, which eliminates problems related to energy transmission,
- environmentally friendly energy sources that do not directly deepen the greenhouse effect and do not emit oxides of sulfur and nitrogen,
- after reimbursement of the generating installation costs there is free energy, no extra fuel costs.

Disadvantages of solar radiation energy (Lewandowski, 2007):

- cyclicality (the need to store energy at the peak of production and use it in times of solar radiation deficiency),
- high cost of photovoltaic panels,
- variable concentration and low intensity,
- the need to support other energy sources,
- large installations occupy very large areas.

Unfortunately, considering photovoltaic power plants we need to remember about whole life-cycle analysis. Despite the fact, that PV technologies goal is to produce energy using renewable source, which is for free and does not produce harmful emissions like carbon dioxide and other greenhouse gases, we need to remember about the process of production of modules and their ultimate disposal. During these processes, a lot of energy from non-renewable resources are used as well as pollution, that have a huge impact on the environment are generated and natural resources are used as raw materials. Circular economy itself, require a change of approach in entire chain. From production, through consumption and disposal to turning wastes into resources and closing the loop supported with business and market change. As the assumptions made by Sica et al. (2018) shows, recovering materials from 100 used panels there are 42 new PV panels that can be produced. (Sica et al., 2018). It presents the potential of this sector in shaping the CE.

When analyzing Polish photovoltaic power plants in terms of data reported by them or by the companies to which they belong, a gap can be noticed. Apart from general information on plant data such as capacity and annual amount of energy produced, it is difficult to find other information. This is undoubtedly related to the characteristics of this power plant. It does not need fuel combustion, as was the case with the types of power plants that were written off earlier.

Consequently, these power plants do not produce pollutants in the form of emitted greenhouse gases, and the only waste during the normal operating cycle of a solar farm is generated after the lifetime of the photovoltaic modules, so during this whole period it can be said that by producing clean energy and not harming the environment. From the point of view of the circular economy, for this type of power plant, the most important thing will be what happens to used panels, what part of them is disposed of, how and how much is recycled primary materials. Table 20 below presents the information that should be included in the reports of PV power plants to calculate the circular economy indicators proposed in Table 21.

Table 20. Data that is recommended for reporting to calculate circular economy indicators for photovoltaic power plants.

Indicator	Unit	Description
En	MJ lub MWh (or multiples)	Total amount of energy produced
P	MW (or multiples)	The installed capacity of power plants
ENSP	MJ lub MWh (or multiples)	The amount of energy produced by solar panel
MT	-	Types of modules used in power plant
EM	-	The amount of exhaused modules
REM	-	The amount of exhausted modules that are recycled
LSP	years	Lifetime of solar panel

Source: Own study

Table 21. Recommended indicators for photovoltaic power plants

Indicator	Unit	Description	Equation	Equation No.
REM%	%	The share of REM in EM		21
SPU	MJ/year	The amount of energy produced by solar panel per its lifetime		22
Eff	%	Efficiency of power plant	This indicator should be reported directly	15

Source: Own study

3.3 How to measure progress in implementation of CE in the energy sector- 2 types of indicators.

When it comes to the energy sector itself, it must be remembered that depending on the analyzed scale (micro, meso, macro) the given coefficients will be different. One cannot evaluate one power plant in the same way as an entire enterprise with 10 of them. Additionally, analyzing one energy-producing unit is only part of the entire chain. and to have a real view of the entire market, it must be understood as one and analyzed the entire life cycle of the material or service. From planning and design to "closing the loop".

However, monitoring the situation and progress on a single link is necessary to have information about the entire process at a later stage. Therefore, this work proposes indicators for exemplary types of power plants. In addition, it is necessary to define the method and method of analyzing the given indicators as they are only variables providing the relevant information in a quantitative or qualitative way. For this purpose, values must be defined that can be referred to or compared (Waas et al., 2014). These can be goals or baseline values.

3.3.1 Inside the 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 is 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. Figures 8-10 show the reduction of fly ash, SO_2 and NO_x for the Belchatow power plant in 1989-2019.

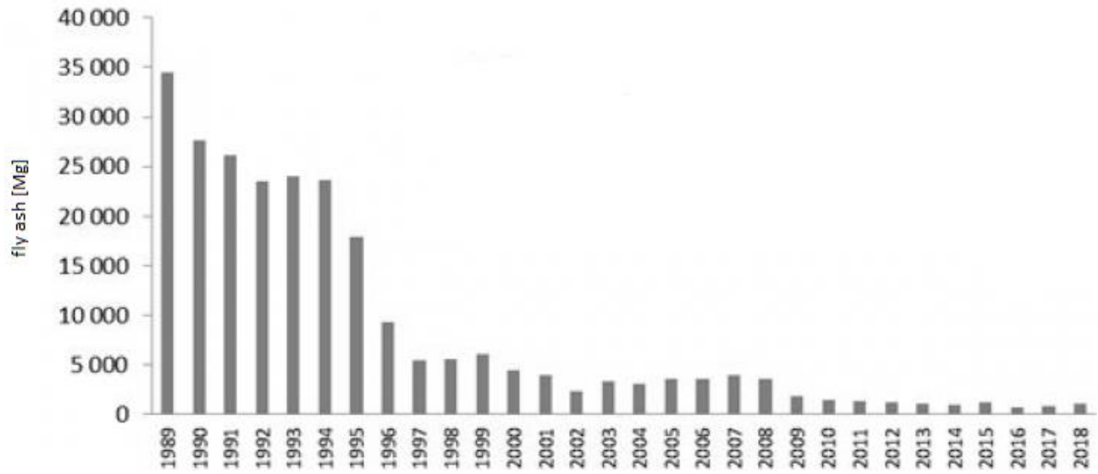

Figure 8. Reduction of fly ash emissions between 1989 and 2018 in Belchatow Power Plant
Source: Belchatow Power Plant official website

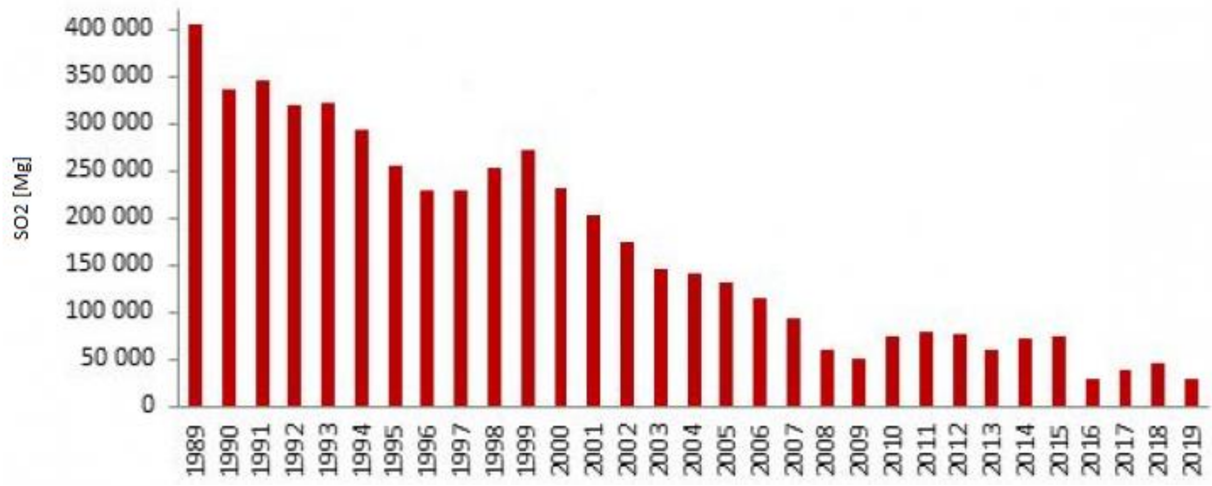

Figure 9.Reduction of SO2 emissions between 1989 and 2019 in Belchatow Power Plant
Source: Belchatow Power Plant official website

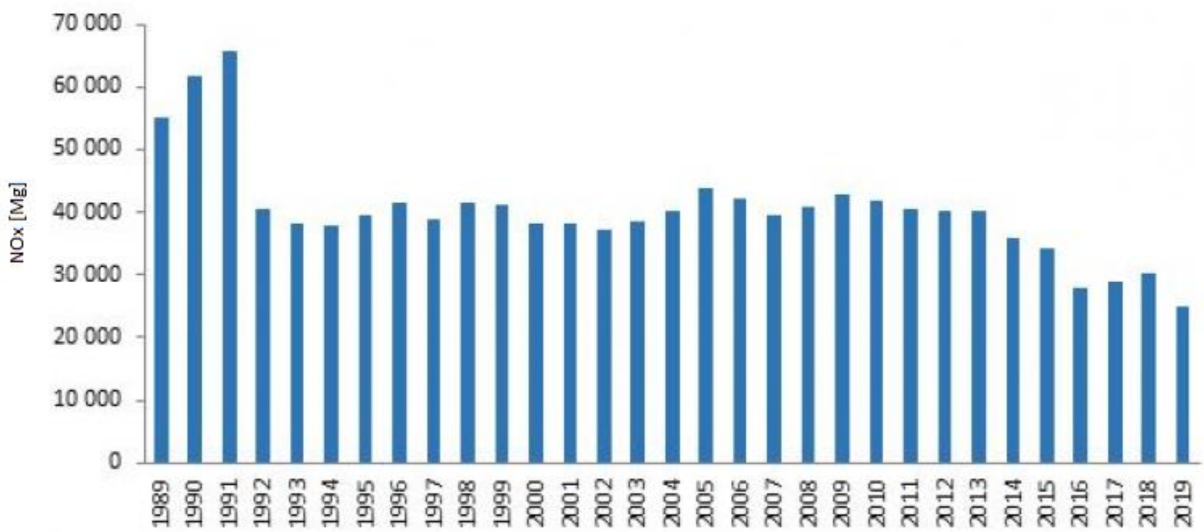

Figure 10. Reduction of NOx emissions between 1989 nad 2018 in Belchatow Power Plant
Source: Belchatow Power Plant official website

Looking at the above figures found on the official website of the Belchatow power plant, 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.

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 information presented, it is difficult to talk about specific values, but it is easy 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.

3.3.2 Different power plants between themselves

The DEA (Data Envelopment Analysis) method was selected as the best method of effectiveness assessment. It is highly useful for measuring effectiveness in various aspects. This method consists in determining the effective unit from among the respondents and the results of the others are related to it. The objects of analysis are Decision Making Units (DMUs). They can be any unit that can transform inputs into outputs. The subject of analysis in this method is the efficiency with which DMUs do it. Because it takes into account the environmental inputs in the environment of the individual, it is possible to reduce random factors and call the method objective (Nazarko, 2008).

The DEA method was first introduced by A. Charnes, W. Cooper, and E. Rhodes in 1978 (Charnes et al., 1978). The mentioned authors used linear programming to estimate technical efficiency measures and created the first model known in the literature as CCR (from the authors' initials) or as CRS DEA (constant return-to-scale, i.e., in connection with the assumption of constant scale effects adopted by the authors). The Debreu-Farrell efficiency measures, which were originally designed to assess efficiency in the situation of using only one input to produce only one effect, in the CCR model were adapted to a multidimensional situation, when the tested units have multiple inputs and outputs. An important contribution of the CCR model to the development of efficiency measures was also the replacement of the current reference point, i.e., the theoretical or hypothetical efficiency limit by the limit determined by the highest observed efficiency among the surveyed units. This change concerns the need to assess the effectiveness of a group of homogeneous decision-making units.

The DEA model does not require the user to define weights in advance for different types of inputs and outputs as with other index methods. It is also not necessary to define a specific function of a given phenomenon as it is the case with the use of statistical methods or econometric regression functions. The DEA method uses linear programming, which allows you to analyze many cases and shows the relationships between them. This makes Data Envelopment Analysis much easier in terms of both analysis and interpretation. An additional advantage is the reduction of the influence of randomness.

The basic premise of this method is to define inputs and outcomes that do not have to be expressed as a cash equivalent. In the context of a circular economy, there may be inputs and outputs that will be positive as well as negative for economic, social or environmental reasons. In addition, there may also be those that are neutral in nature, and therefore have no value in a specific analysis (Adamczyk & Nitkiewicz, 2018).

To compare the efficiency of the transformation of power plants towards a circular economy, a classic CCR model is proposed, for which power plants would be DMU_j, $j=1, 2, ..., n$, that consumes m non-resource inputs $X_j= (x_{1j}, ..., x_{mj})$ and k resources inputs $E_j= (e_{1j}, ..., e_{kj})$ to produce s desirable outputs $Y_j= (y_{1j}, ..., y_{sj})$ and p undesirable outputs $B_j= (b_{1j}, ..., b_{pj})$. The efficiency is defined as a ratio of the sum of weighted outputs to the sum of the weighted inputs. Then, Equation 1 is used to measure the efficiency of j^{th} DMU.

DEA ratio model:

$$Eff = MAX \frac{\sum_{i=1}^{m} v_i x_{ij} + \sum_{l=1}^{k} w_l e_{lj}}{\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj}}$$

$$\frac{\sum_{i=1}^{m} v_i x_{j0} + \sum_{l=1}^{k} w_l e_{lj}}{\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj}} \leq 1 \tag{23}$$

$$u_r \geq 0, v_i \geq 0, w_l \geq 0, q_t \geq 0, r = 1, \dots, s, i = 1, \dots, m, l = 1, \dots, k, t = 1, \dots, p$$

where u_r, u_i, w_l, q_t are weights attached to r^{th} desirable output, t^{th} undesirable output, i^{th} non-resource input and l^{th} resource input.

Transformation from above fractional model to a linear programming can be easily done. The efficiencies can be measure with the reference to production possibility so there are two models. Equation 24 presents input-oriented model and Equation 25 output-oriented model.

DEA weights model, input-oriented:

$$Eff = MAX \left(\sum_{i=1}^{m} v_i x_{ij} + \sum_{l=1}^{k} w_l e_{lj} \right)$$

$$\left(\sum_{i=1}^{m} v_i x_{ij} + \sum_{l=1}^{k} w_l e_{lj} \right) - \left(\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj} \right) \leq 0 \tag{24}$$

$$\left(\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj} \right) = 1$$

$$u_r \geq 0, v_i \geq 0, w_l \geq 0, q_t \geq 0, r = 1, \dots, s, i = 1, \dots, m, l = 1, \dots, k, t = 1, \dots, p$$

DEA weights model, output-oriented:

$$Eff = MIN \left(\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj} \right)$$

$$\left(\sum_{i=1}^{m} v_i x_{ij} + \sum_{l=1}^{k} w_l e_{lj}\right) - \left(\sum_{r=1}^{s} u_r y_{rj} + \sum_{t=1}^{p} q_t\, b_{tj}\right) \le 0 \tag{25}$$

$$\left(\sum_{i=1}^{m} v_i x_{ij} + \sum_{l=1}^{k} w_l e_{lj}\right) = 1$$

$$u_r \ge 0, v_i \ge 0, w_l \ge 0, q_t \ge 0, r = 1, \dots, s, i = 1, \dots, m, l = 1, \dots, k, t = 1, \dots, p$$

As the model CRR cannot work on data with undesirable outputs in DEA, there are some approaches developed to overcome this problem. Treating the undesirable outputs as inputs is one of them and as it is widely used, it is also proposed for this analysis. However, keeping in mind the ideas of CE and their objectives the modification in this approach had to be done. Circularity means reusing, reducing, and recycling of undesirable outputs as secondary materials, which are a new input, and decreasing the undesirable outputs. Therefore, *p* undesirable outputs B_j= (b_{1j}, ..., b_{pj}) needs to be transformed into input so the model can be modified:

$$MAX \sum_{r=1}^{s} u_r b_{r0}$$

$$s.t. \sum_{i=1}^{m} v_i x_{i0} + \sum_{l=1}^{k} w_l e_{l0} = 1, \tag{26}$$

$$\sum_{r=1}^{s} u_r b_{r0} - \left(\sum_{i=1}^{m} v_i x_{i0} + \sum_{l=1}^{k} w_l e_{l0}\right) \le 0,$$

$$u_r \ge 0, v_i \ge 0, w_l \ge 0, r = 1, \dots, s, i = 1, \dots, m, l = 1, \dots, k$$

where u_r, u_i, w_l are weights attached to rth output, ith non-resource input and lth resource input.

Input oriented method was successfully implemented in China to measure the effectiveness of the policy of circular economy (Hua-qing Wu, 2013). Unfortunately, due to lack of information about the polish power plants further calculations of this proposal are not presented. In Tables 14,18 and 20 were recommended information to report by power plants. Besides them, some additional information about inputs and outputs of energy production are required. Propositions are presented in Table 22 below.

Table 22. Additional information for DEA method

Additional information for DEA method		
Emp	-	The amount of hired staff as a cost of produced energy
Sav	mln EUR	The amount of money saved due to implementation of circular economy ideas
In	mln EUR	The amount of money invested in pro-ecological projects, environmental protection, renewable energy sources or modernization and development of the existing infrastructure to increase energy efficiency
SI	mln EUR	The amount of money invested in social initiatives related to environmental protection, emissions, waste, energy awareness and other issues related to the circular economy

Source: Own study

The use of the DEA method, as described above, is not possible in a situation where such a large amount of data from the power plant is missing. This is a more advanced method of measuring the transformation towards a circular economy by comparing power plants with each other, unfortunately in this case a simplified method must be used, which may be based on comparing the absolute ratios of the same type of power plant. For the data found and the calculated coefficients it is a difficult task as only the values of two coefficients can be compared (out of 12 of which an attempt was made to calculate). It is impossible to carry out a full analysis on this basis, and you can only treat it as a guide in future attempts.

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.

4. Results and discussion

4.1 Indicators inside the power plant

4.1.1 Analysis of results for Belchatow Power Plant

Based on the collected and presented in paragraph 3.4.2 information about reduction of fly ash, SO_2 and NO_x, there was an attempt made to calculate possible indicators. As the figures 8-10 do not show the exact values of emission an estimation was made, and the data used further to calculations are presented in Table 23 below.

Table 23. 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: Own study

For estimated data for Belchatow Power Plant, using formulas 9, 11 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 24 below. 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 24. 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 25 below, this change is presented. The values were calculated using the equation:

$$Change = \frac{V_{year}}{V_{year-1}} - 1 \quad (25)$$

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 25. Change of the indicators value in compare to previous year.

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 25 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.

One of the proposed indicators are tracked from 1989 by Belchatow power plant itself and the results are presented in the Figure 11. Power plants presents accumulated data for the reduction of CO_2 emissions per MWh, which stays for I_{EmCO2} proposed.

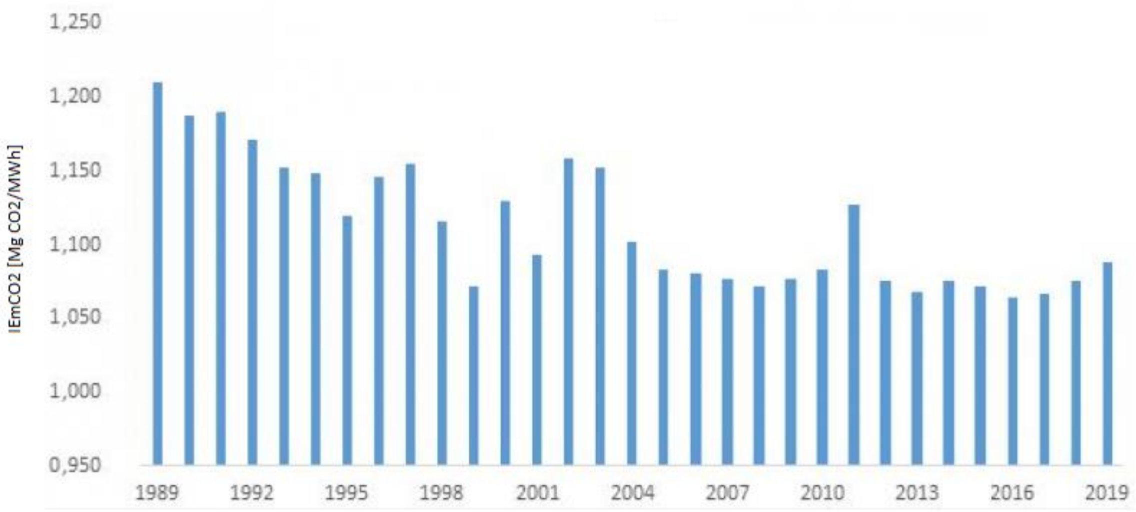

Figure 11. CO_2 emissions indicator for Belchatow Power Plant between 1989 and 2019
Source: Belchatow Power Plant official website

From the Table 25 and Figure 11, 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 example 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, you 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 is progressing. However, given such limited data, it cannot be clearly stated and classified as a part of the circular economy assumptions.

4.1.2 Analysis of results for Drax Power Station

As a comparison of polish power plants there was Drax Power Station taken under consideration as an example from Great Britain. At this moment it is more biomass power plant than coal, because in 2019 77% of energy was generated from biomass when in 2013 it was 11% with 89% generation based on hard coal. It is an example how conventional power plants can proceed to reduce negative impact on environment following the sustainable development and circular economy goals. The power plant generating electricity mostly from coal, changed their policy and from few years they are successfully transform their profile with a huge positive effect on CO_2 emissions which can be seen on the Figure 12 below.

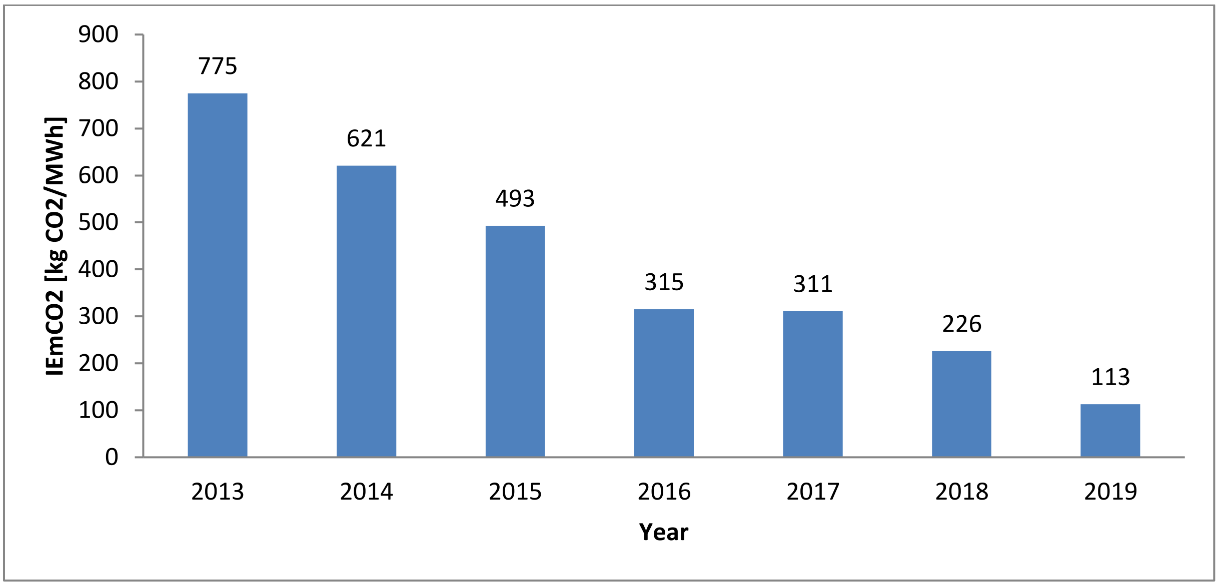

Figure 12. CO_2 emissions indicator for Drax Power Station between 2013 and 2019
Source: Drax Power Station official website

In the Figure 12 the progress toward being carbon negative is presented. This is goal for Drax Power Plant to be reached by 2030. As we can see, they are doing very well and from the trend presented above we can assume that they will manage to do this. Their ambitious plant influences circular economy transformation. In last few years Drax PS has turned from coal-based energy generation and are focused mostly on biomass right now. It may be a good example for other conventional power plants and way to follow, because the emissions that they were able to decrease are enormous. From 2013 the emissions of CO_2 per MWh decrease of 85% and only looking at last 2 years there is 50% difference. Unfortunately, this is the only indicator that is reported in that scale so we can see its progress over last years. The rest of data is presented in the same way as in polish examples, so the decision, whether this power plant follows the circular economy ideas, is impossible to make. Looking at their CO_2 emission indicator it can be assume the transformation is proceeding with a good effect, but it is pushed rather by different motivations than circular economy itself. It is the second example that shows that the data availability is crucial.

4.2 Indicators to compare different power plants

When analyzing Polish power plants in terms of the indicators they report, it can be noticed that this is not practiced. If we consider the data on the operation of power plants themselves in terms of environmental, economic and social aspects, concrete figures can only be obtained on environmental topics. These are scarce data focused mainly on fly ash and greenhouse gas emissions. It is difficult to find information on topics related to water, sewage, or combustion by-products. When it comes to economic and social issues, they are mentioned only in general terms, and more information can be obtained in the reports of the companies that own the power plants.

However, this information is not specific to each unit, but pertaining to the entire enterprise. On this basis, it can be said that the analysis of the reported indicators of the circular economy would have a greater effect now if it were compared to a larger scale. The information found on the official websites of the power plants concerned is included in Table 26 for further use in the calculation of the proposed circular economy indicators. Due to the poorly developed reporting system, the data found only concern hard coal and lignite mines.

There is no specific information on power plants burning biomass individually. Photovoltaic power plants on the Polish energy market, now, do not play the most important role. They are small compared to coal-fired power plants, and those that operate on a larger scale than domestic power plants do not report their activities. Now, however, based on the proposed indicators, it is not necessary to thoroughly analyze this type of energy due to the short period of operation of these installations in Poland.

Table 26. Data from coal power plants

Information/indicator	Power Plant					Unit
	Belchatow	Kozienice	Rybnik	Turow	Drax	
Data						
Type of fuel	lignite	hard coal	hard coal	lignite	hard coal/biomass	-
Installed capacity	5298	2840	1720	1505	3069	MW
Energy produced	32.5	11	6	13	15	TWh
CCPs	-	-	764 771	1 230 836	-	Mg
Reuse of CCPs	-	-	659 670	1 230 836	-	
Emission of fly ash	700	247	226	245	35/415	Mg
CO_2 eq .emissions	-	-	-	-	2.38	mln Mg
SO_2 emissions	30 000	7 442	2 549	2 204	601/986	Mg
CO_2 emissions	-	9 728 131	-	5 427 827	1.96	Mg
NO_x emissions	25 000	7 645	-	3 724	746/7104	Mg
CO emissions	-	-	-	286	-	Mg
Amount of water used	-	-	-	-	177	mln m^3
Amount of waste water	-	-	-	2 655	-	mln m^3
Indicators						
SO2 emissions	0.995	0.659	-	-	-	kg/MWh
NOx emissions	0.829	0.677	-	-	-	kg/MWh
Fly ash emissions	0.022	0.022	-	-	-	kg/MWh
CO emissions	0.651		-	-	-	kg/MWh
CO_2 emissions	1084	0.862	-	-	113	kg/MWh
$CO_{2\,eq.}$ emissions	-	-	-	-	137	kg/MWh
Eff	39% (42%)	38% (45%)	-	NA (42%)	-	%

Source: Own study based on official power plants' websites

The above table contains information about the Belchatow, Kozienice, Rybnik, Turow and Drax power plants. As mentioned before, they concern their environmental impact with an emphasis on fly ash and greenhouse gas emissions. However, they are not complete in this list. Apart from the Turow power plant, which reports all the above-mentioned data, there are gaps.

On the other hand, only Drax reports greenhouse gases emissions in a form of the CO_2 equivalent, which should the most common practice. The data presented on websites is very selective. The Bełchatow Power Plant does not use specific values while providing data, but only approximations. Looking at all of those 5 power plant's official websites the English one present the best and most complete data, but also has many missing information. The second part of Table 26 shows the emission factors that have been found that fit into the list of recommended circular economy indicators, as well as partial information about the power plant's efficiency. Only two of them presents data for whole power plant. The value in parenthesis state for the most modern block of power plant. Low general value is the reason of old technologies used. We need to remember that mentioned power plant has been active for a long time and most of the blocks were built about the end of XX century. Now, constant improvements and modernizations are happening, and new block are built with the newest technology.

Based on the proposed indicators for power plants operating on hard coal or lignite (Table 16 and Table 15), formulas 1-13 and the real data found and presented above (Table 26), calculations were made. Their results are presented in Table 27.

Table 27. Results of calculations of proposed indicators for coal power plants.

Indicator	Power Plant					Unit
	Belchatow	Kozienice	Rybnik	Turow	Drax	
LCC%	N/A	N/A	N/A	N/A	N/A	%
EnLCC	N/A	N/A	N/A	N/A	N/A	%
I_{Wa}	N/A	N/A	1275	947	N/A	kg/MWh
Wa_N%	N/A	N/A	N/A	N/A	N/A	%
Wa_{RC}%	N/A	N/A	N/A	N/A	N/A	%
Wa_{RCo}%	N/A	N/A	N/A	N/A	N/A	%
I_W	N/A	N/A	N/A	N/A	11.8	mln m^3/TWh
I_{Ww}	N/A	N/A	N/A	204	N/A	mln m^3/TWh
NWw%	N/A	N/A	N/A	N/A	N/A	%
CCPs%	N/A	N/A	86%	100%	N/A	%
I_{Fa}	0.022	0.022	38	0.019	0.300	kg/MWh
I_{Em}	N/A	N/A	N/A	N/A	158.6	kg eq CO_2/MWh
I_{EmSO2}	0.92	0.68	0.42	0.17	0.11	kg SO_2/MWh
I_{EmCO2}	1084	884	N/A	417	130.6	kg CO_2/MWh
I_{EmNOx}	0.77	0.67	NA	0.29	0.52	kg NO_x/MWh
I_{EmCO}	0.651	N/A	N/A	0.022	NA	kg CO/MWh

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.

When looking at the results obtained in the attempt to calculate the proposed indicators, it should be remembered that 4 of these power plants base their production on conventional energy sources, i.e., hard coal or lignite. On the other hand, the Drax power plant is an example of a transformation from a conventional power plant to a biomass power plant with the goal of being carbon negative. This means removing more CO_2 from the atmosphere than it produces. This is possible thanks to investing in biomass, which is neutral in this respect. The results of Polish power plants 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.

4.3 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, on a scale considering exemplary companies, 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, a few indicators for coal, biomass and photovoltaic power plants were proposed and an attempt was made to calculate them for the purpose of final evaluation and checking their usefulness. Going a step further and looking for specific information about the power plants themselves, there is much less information available than in the case of a larger scale. For this reason, an attempt was made to calculate and further analyze only coal-fired power plants. In the first case, for the Belchatow power plant, as an example to check the transformation within one power plant, the example of the Great Britain- Drax Power Station power plant was used for comparison, followed by a comparison between the available power plants. The first example, the

Belchatow, power plant, 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, however, 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 idea of changing a linear economy into a circular economy, but a positive effect dressed up by others transformation. Many of its ideas coincide with other changes and requirements that have been dictated by power plants over the years. An example of Drax Power Station, unfortunately due to the lack of relevant data on only one CO_2 emission factor, how positive in this respect is the change from coal to renewable energy sources such as biomass. Such a change could be the most effective form, but its further evaluation and verification should be carried out. Due to the circular economy, switching from fossil fuel to biomass, which is considered CO_2 neutral, would significantly reduce the negative environmental impact of such power plants and the number of natural resources used. On the other hand, huge tracts of land would have to be designated for energy purposes, which would have further consequences. Although this seems to be a very good way to achieve this transformation, you need to remember to keep the balance in the entire market.

Looking at the results of the analysis of the comparison among different power plants and compressing Table 27 to list the calculated values for different power plants, the following Table 28 is obtained.

Table 28. The sum of the results of the proposed indicators calculation

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

What can be noticed from the table above, for 5 exemplary power plants, only 2 indicators could be calculated for all of them. They were I_{Fa} and I_{EmSO2}. On this basis, it is difficult to draw specific conclusions, but looking at the results obtained in the table above as a whole, the Drax power plant is characterized by by far the lowest greenhouse gas emissions. Its overall emissions, presented in CO_2 equivalent, are lower than the CO_2 emissions in other mines (except for the Rybnik power plant, where the data could not be obtained). Due to the type of fuel used in these plants, the natural conclusion that comes to mind is that the Drax plant is the most suited to the circular economy concept mentioned. However, it is not known what the power plants do with waste and how they treat combustion by-products, only Turow and Rybnik power plants report a CCPs% ratio which is definitely very important as it represents keeping the materials in circulation, adding further use to them. In addition to environmental issues, there are also others, such as economic and social, that are not micro-accessible and can be found in company-wide reports. 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.

As for the recommended indicators themselves, their limitations are reduced to the type of power plant. As can be seen from the example of the discussed power plants, they can be used both in Poland and other countries. In this case, it was Great Britain. The conducted analysis would not work in the case of other types of power plants, such as photovoltaic power plants (for this case the indicator in Table 18 has been proposed), 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 different. Under ideal conditions, having a complete set of data to carry out a detailed analysis, knowing the boundaries or even basic requirements of CE, using the recommended indicators, you can decide whether the power plant is linear or circular.

The presented analysis, due to a few existing limitations as well as the unclear definition of the circular economy itself and its boundaries, can be considered preliminary and giving a picture of the general problem and the need to find its solution. The idea of a circular economy should be spread, and cooperation from companies, in this case from power plants, is needed to measure the transformation towards it. The first step in further research in this direction should be to clearly define the boundaries of the circular economy. Without it, it is impossible to determine whether a given power plant is already circular or not. 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. To compare power plants with each other, the DEA method seems to be a very good solution, so it would be ideal to extend the information provided with that contained in Table 19.

5. Conclusions

The circular economy is a tool that, together with renewable energy sources, on this example of the presented biomass, will 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. In addition to food production, it is secondarily used for energy purposes through combustion and co-incineration. Looking at the CE assumptions, they are not fully met because 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 the growing awareness of the public about environmental pollution, and moreover, the opportunities to improve the economy, make the circular economy an inevitable future. As CE is a tool for implementing the idea of the European Green Deal and is an element necessary to achieve the objectives of the project, 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. Failure to properly manage waste and use resources will lead to environmental pollution, forcing people to live in a dirty, polluted, and toxic space. An important point in the entire transformation of the linear economy into a circular economy are appropriate legal sanctions, programs supporting this change and documents such as: *Closing the loop - An EU Action Plan for the Circular Economy, The European Commission; Poland's energy policy until 2040, The Ministry of Climate and Environment or The National Energy and Climate Plan for 2021-2030, The Ministry of State Assets.* The 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 certainly be faced in the coming years will be the restructuring of the energy sector towards low-emission energy, which should become more and more popular and attractive, and additionally, 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, while maintaining its balance. 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.

Bibliographic References

Adamczyk, J., Nitkiewicz, T. 2008. DEA as a method for assessing sustainable development in energy enterprises. [in:] Ecology Problems (*Problemy Ekologii*) 2008: 9-16.

Bachorz, M. 2017. Poland's road to a circular economy: description of the situation and recommendations (*Polska droga do gospodarki o obiegu zamkniętym: opis sytuacji i rekomendacje*). Closed Circular Economy Institute.

Bernet-Kowalska, G., Jurgas, A., Kacprowska, J., Pawelczyk, M., Szymanska, M. Warsaw 2019. Energy from renewable sources in 2018. Statistics Poland.

Bielecka, A. Cracow 2017. Circular Business Models in Energy Sector. Scientific Journals of the Humanitas University. Management (*Zeszyty Naukowe Wyższej Szkoły Humanitas. Zarządzanie*).

Bielecka, A., Avidiushechenko, A., Kulczycka, J., Smol, M. Opole 2018. Application of the circular economy in the power sector of Malopolska Region- benefits and challenges

Bist, N., Sircar, A. and Yadav, K. 2020. Holistic review of hybrid renewable energy in circular economy for valorization and management. [in:] Environmental Technology & Innovation vol. 20.

Bochenek, D. Warsaw 2018. Environment 2018. Statistics Poland, Spatial and Environmental Surveys Department.

Bukowski, H. and Sznyk, A. Cracow 2019. Development of a methodology and identification of circular economy indicators for the Polish economy in a regional perspective (*Opracowanie metodyki i identyfikacja wskaźników gospodarki o obiegu zamkniętym dla gospodarki polski w ujęciu regionalnym*). [in:] Circular economy in politics and research (*Gospodarka o obiegu zamkniętym w polityce i badaniach naukowych*), edit. Kulczycka J.

Charnes, A., Cooper, W.W., Rhodes E. 1978, Measuring the efficiency of decision-making units. [in:] European Journal of Operational Research 429-444.

Chrzanowski, Z., Masłowski, D. 2014. Re-use Coal Combustion Products in Poland (*Zagospodarowanie ubocznych produktów spalania w Polsce*). [in:] Materiały Budowlane vol 12.

Dygas, P i Generowicz, N. Cracow 2020. Identification of indicators in the field of circular economy reported by domestic and foreign companies from the energy sector (*Identyfikacja wskaźników z zakresu gospodarki o obiegu zamkniętym raportowanych przez firmy krajowe i zagraniczne z branży energetycznej*). [in:] Circular economy monitoring indicators (*Wskaźniki monitorowania gospodarki o obiegu zamkniętym*).

Elia, V.,Gnoni Grazia, M., Tornese,F. Lecce 2016. Measuring circular economy strategies through index methods: A critical analysis, Journal of Cleaner Production (2016).

Ellen MacArthur Foundation, 2013. Towards the Circular Economy. Economic and business rationale for an accelerated transition.

European Academies Science Advisory Council (EASAC). Germany 2016. Indicators for a circular economy, EASAC policy report vol 30.

Geng Y., Doberstein B. 2008. Developing the circular economy in China: challenges and opportunities for achieving leapfrog development. [in:] International Journal of Sustainable Development and Planning vol. 15:231-239.

Geng Y., Fu J., Sarkis J., Xue B. 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. [in:] Journal of Cleaner Production vol. 23:216-224.

Gutmann, K., at all. 2014. Europe's Durty 30. How the EU's coal-fired power plants are undermining its climate efforts.a

Hodana, M., Holtzer, G., Kalandyk, K., Szymanska, A. Cracow 2012. Renewable energy sources - a guide (*Odnawialne źródła energii- poradnik).*

Hua-qing Wu,Yan Shi, Qiong Xia, Wei-dong Zhu. 2013, Effectiveness of the policy of circular economy in China: A DEA-based analysis for the period of 11th five-year-plan. [in:] Resources, Conversation and Recycling vol. 83:163-175.

Iacovidou E., Velis C.A., Purnell P., Zwirner O., Brown A., Hahladakis J., Millward-Hopkins J., Williams P.T. 2017. Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: a critical review. [in:] Journal of Cleaner Production 2017 vol.166:910–938.

Kalmykova Y., Sadagopan M., Rosado L. 2018. Circular economy – From review of theories and practices to development of implementation tools. [in:] Resources, Conservation and Recycling col 135:190-201.

Korhonen, J., Honkasalo, A. i Seppälä, J. 2018. Circular Economy: The Concept and its Limitations. [in:] Ecological Economics vol. 143:37-46.

Kirchherr J., Reike D., Hekkert M. 2017. Conceptualizing the circular economy: an analysis of 114 definitions. [in:] Resources, Conversation and Recycling vol.127:221–232.

Kulczycka J., Cracow 2020, Circular economy monitoring indicators (*Wskaźniki monitorowania gospodarki o obiegu zamkniętym*).

Kulczycka, J., Nowaczek, A., Pedziwiatr, E., Henclik, A. Cracow 2019. "Oto - GOZ": Circular economy measures in strategic documents of selected countries (*Oto - GOZ: Mierniki gospodarki o obiegu zamkniętym w dokumentach strategicznych wybranych krajów*).

Lewandowski, W.M. Warsaw 2007. Pro-ecological renewable energy sources (*Proekologiczne odnawialne źródła energii*).

Macuk R. 2020. Energy transformation in Poland. 2020 edition (*Transformacja energetyczna w Polsce. Edycja 2020*).

Mayer A., Haas W., Wiedenhofer D., Krausmann F., Nuss P., Blengini G.A. 2018. Measuring

Progress towards a Circular Economy. A Monitoring Framework for Economy-wide Material Loop Closing in the EU28. [in:] Journal of Industrial Ecology vol. 23:62-76.

Moldan B., Janoušková S., Hák T. 2011. How to understand and measure environmental sustainability: indicators and targets. [in:] Ecological Indicators 17:4-13.

Moraga G., Huysveld S., Mathieux F., Blengini G. A., Alaerts L., Van Acker K., de Meester S., Dewulf J. 2019. Circular economy indicators: What do they measure? [in:] Resources, Conservation and Recycling vol 146:452-461.

Nazarko, K., Jakuszewicz, I., Urban, J., Warsaw 2008, DEA method in the analysis of production units (*Metoda DEA w analizie jednostek produkcyjnych*).

Potting J., Hanemaaijer A., Delahaye R., Ganzevles J., Hoekstra R., Lijzen J.; The Hague: 2018. Circular Economy: What We Want to Know and Can Measure - System and baseline assessment for monitoring the progress of the circular economy in the Netherlands. PBL Netherlands Environmental Assessment Agency.

Pottin, J., Nierhoff, N., Montevecchi, F., Antikainen, R., Colgan, S., Hauser, A., Günther, J., Wuttke, J., \Jørgensen Kjær, B. i Hanemaaijer, A. 2017. Input to the European Comission from European EPAs about monitoring progress of the transition towards a circular economy in the European Union.

Priyadarshini, P. i Abhilash, P.C. 2020. Circular economy practices within energy and waste management sectors of India: A meta-analysis. [in:] Bioresource Technology vol. 304.

Rosiek, J. Opole 2018. The implementation of Circular Economy Concept in the Polish Coal Combustion Products Sector- selected problems. [in:] Economic and Environmental Studies 2018 vol 18:353-373.

Saidani, M., Yannou, B., Leroy, Y., Cluzei, F. 2019. A taxonomy of circular economy indicators. [in:] Journal of Cleaner Production vol 207:542-559.

Sica, D., Malandino, O., Supino, S., Testa, M., Lucchetti, C., 2018. Management of end-of-life photovoltaic panels as a step towards a circular economy. [in:] Renewable and Sustainable Energy Reviews vol 82.

Tomić, T. i Schneider, D.R. 2018. The role of energy from waste in circular economy and closing the loop concept – Energy analysis approach. [in:] Renewable and Sustainable Energy Reviews vol. 98:268-287.

The European Commission. Brussels 2015. Closing the loop- An EU action plan for the circular economy

The European Commission. Strasburg 2018. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on a monitoring framework for the circular economy.

The European Commission. Brussels 2019. Communication from the Commission. The European Green Deal.

The Council of Ministers, Warsaw 2019. Roadmap for transformation towards a circular economy (*Mapa drogowa transformacji w kierunku gospodarki o obiegu zamkniętym*).

The Ministry of Climate and Environment. Warsaw 2019. Poland's energy policy under 2040 (*Polityka energetyczna Polski do 2040r.*).

The Ministry of State Assets. Warsaw 2019. National plan for energy and climate for 2021-2030 (*Krajowy plan na rzecz energii i klimatu na lata 2021-2030*).

Waas T., Hugé J., Block T., Wright T., Benitez-Capistros F., Verbruggen A. 2014.Sustainability Assessment and Indicators: Tools in a Decision-Making Strategy for Sustainable Development. [in:] Sustainability vol.6:5512-5534.

Zhen Wei, Zhenxing Chang, Chong Chen. 2020. Sustainable development of coal-based circular economy park: a case study. [in:] E3S Web of Conferences 145(1):02064.

Websites literature:

European Environment Agency: Indicators https://www.eea.europa.eu/themes/energy/indicators#c7=all&c5=all&c10=&c13=20&b_start=0, date 12.12.2020.

European Environment Agency. (2019. Power engineering *(Energetyka)* (https://www.eea.europa.eu/pl/themes/energy/intro, date: 12.12.2020.

The European Commission. 2020. Renewable enegy in the EU in 2018. https://ec.europa.eu/eurostat/documents/ 2995521/10335438/8-23012020-AP-EN.pdf/292cf2e5-8870-4525-7ad7-188864ba0c29. Last acess12.12.2020.

The European Commission. Brussels 2015. Closing the loop: The Commission has adopted an ambitious economic package closed circuit, the purpose of which is to stimulate competitiveness, creating jobs and promoting sustainable economic growth *(Zamknięcie obiegu: Komisja przyjęła ambitny pakiet dotyczący gospodarki o obiegu zamkniętym, którego celem jest pobudzanie konkurencyjności, tworzenie miejsc pracy i wspieranie trwałego wzrostu gospodarczego).* https://ec.europa.eu/commission/presscorner/detail/pl/IP_15_6203, date: 12.12.2020.

The European Commission. Circular economy- Overview https://ec.europa.eu/eurostat/web/circular-economy, date: 12.12.2020.

Rybnik Power Plant official website: https://elrybnik.pgegiek.pl, date: 19.12.2020.

Turow Power Plant official website: https://elturow.pgegiek.pl, date: 19.2020.

Belchatow Power Plant official website: https://elbelchatow.pgegiek.pl, date: 19.12.2020.

Kozienice Power Plant official website: https://elektrowniakozienice.com, date: 19.12.2020.

Drax Power Station official website: https://www.drax.com, date 21.12.2020.

Sphera website: gabi-software.com/france/solutions/gabi-envision/, date: 29.01.2021.