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ANALYZING AND ASSESSING THE ENVIRONMENTAL IMPACTS OF ENERGY PRODUCTION

Humanity's vision of designing energy production technologies by using diverse energy resources has been oriented to steadily increasing its quality of life. Registered developments have however emphasized that economic activities can have besides positive desired impacts on humanity's quality of life negative undesired effects. In the present time of sustained debates regarding appropriate energy supply systems needed to be designed in the future, it is relevant to consider not only the availability of corresponding needed energy resources but also their environmental impacts. The process of analyzing and assessing the environmental impacts of energy supply systems must be carefully carried out by considering fossil fuels and more recently renewable energy resources. In this context, an environmental impact analyzing model because of using energy resources must be coupled with an assessing model finally resulting in an integrative model. Applying a designed integrative model future usage odds of energy resources will be shaped by considering the currently debated European Green Deal to ensure sustainable energy production.

1. INTRODUCTION

The world we live in is experiencing rapid development in different fields and the power supply industry is facing an unprecedented change to become a sustainable one. Alongside the objectives of decarbonisation, digitalisation and decentralisation already undertaken as an industry, together with the promotion and commitment of the European Green Deal [1], the energy industry has recently faced other two major challenges, i.e., two crises, induced by the COVID-19 pandemic and the other one referring to the energy prices. Certainly, a pretty unstable geopolitical situation in the world means new

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risks for the energy sector and may bring new challenges to this industry and beyond. The current imbalances caused by the energy sector crisis and geopolitical instability are putting significant pressure on the electricity generation, distribution, and supply chain.

The unproblematic easy access to electricity and thermal energy represents an essential element in ensuring general well-being, providing the basis for a range of economic activities, and ensuring citizens a high standard of living, mobility, and social comfort. At the same time, considering methods currently used on a large scale being mostly based on fossil fuels means that electricity generation and consumption create significant and ongoing pressure on the environment by polluting it through the release of gases into the air, in particular greenhouse gas. There is also land cover and land degradation, waste is generated, or accidental pollution occurs. All these affect natural ecosystems and the environment, leading to current climate change that is being increasingly felt, to growth in global average temperature and not least to negative effects on human health [2–4].

Romania, like most countries, relies on fossil fuels (coal, oil, natural gas) to meet and secure energy needs on the national level. The combustion of such fuels within thermal power plants leads to air pollution once the heat is released, i.e., thermal energy is converted into electricity by the corresponding generators. This pollution occurs by carbon from fuels chemically reacting with oxygen from the atmosphere, producing CO_2, which is released into the air. Other air pollutants such as sulphur dioxide, SO_2, nitrogen oxides NO_x, and dust are also released into the air with an impact on air quality. Thermal power plants with an installed power of more than 50 MW (large combustion plants – LCP) are responsible for about 40% of the electricity generation capacity in the European Union. They are dependent on fossil fuels and their operation results in pollutants emissions into air, water, and soil, with harmful effects on the ecosystems [5]. The impact of the energy sector on the environment is thus significant, especially when referring to electricity generated from fossil fuels, being the reason why addressing sustainability in this sector is a particularly burning issue [2, 6–8].

Given the crisis caused by COVID-19, the European Commission created a *Recovery and Resilience Mechanism* to provide efficient and significant financial support to accelerate the implementation of sustainable reforms and related public investments in the Member States. The *National Recovery and Resilience Plan* (NRRP) of Romania is the strategic document underpinning reform priorities and investment areas for the implementation of the recovery and resilience mechanism [9]. The general objective of the NRRP is to develop Romania through the implementation of key programs and projects supporting resilience, crisis preparedness, adaptability, and development potential, through major reforms and key investments with funds allocated to Romania [9].

Significant reductions in pollutant emissions are expected in the coming years, both because of more stringent conditions on emissions generated by large combustion plants and due to the implementation of energy policy and climate change mitigation strategies that stimulate the use of renewable energy resources to achieve the EU's goal of becoming a climate neutral continent by 2050 [5, 8].

2. MATERIALS AND METHODS

2.1. MODELLING VARIOUS TECHNOLOGICAL APPLICATIONS

Modelling technological applications has proven over the years to be particularly useful, as it allows operating mode revisal of analysed technology, as well as identifying appropriate measures, which should be applied for improving analyzed technology operation, anyway before practical implementation of analysed technological application [3, 6, 10–13, 15]. This process is particularly relevant in the case of large financial investments towards the realisation of a specific technological application [6, 11]. This is the common situation of many technologies including the ones for energy resources usage, regardless of the type of considered resources, whether fossil fuels or renewable resources [6, 7, 14]. Unlike this background, it should be noticed that the process of modelling and simulation of various technological applications before their implementation has substantially developed in recent times with advance assured in terms of shaping specific software needed to design such mathematical models and to carry out specific simulations used in this regard [11, 15–17].

Once it has become clear that various technological applications may have a certain impact on the environment, perhaps already in the development phase or perhaps in the use phase, as well as in the decommissioning phase, if one considers the numerous debates currently taking place on nuclear power plants, it has been accepted that there is a need to analyze and assess the potential impact of developing and using various technological applications [2, 6, 11, 14, 18]. The intention is to try to understand the potential environmental impact of the use of a particular technology, recognizing, and considering in an early stage existing possibilities to reduce this impact. By this procedure it should be avoided waiting until that impact becomes a reality, as happened many times in the past and is happening even today, considering recent debates on the greenhouse effect and global warming. In our pretty complex present society, there is a need to try modelling technological applications and their impacts by considering not only technological and economic fields but also environmental and social ones. This means that designed models should integrate various aspects from different fields, such as technological, economic, but also environmental and social ones [6, 11–13, 19]. A widely accepted definition for such integrative models was given by Mesarovic, who claimed in 2000 during a lecture at a TERRA project meeting that *integrative models are such models that incorporate knowledge from more than one field of study* [17].

Integrative modelling represents the process of horizontal and vertical integration of different aspects of interest to be considered for the analyzed case that may come from different domains [11]. Going into detail, integrative models are such models that may have many elements coming from various fields and there are many interdependencies between the underlying system elements [19]. In the process of developing integrative models, systems theory concepts play a particularly important role, as they often involve physical quantities from different domains that can only be interconnected by applying concepts coming from systems theory [3, 6, 11, 19].

2.2. MODEL FOR ANALYZING AND EVALUATING ENVIRONMENTAL IMPACTS OF TECHNOLOGIES FOR USING ENERGY RESOURCES – MAEEITUER

The proposed model for analyzing and evaluating the environmental impacts of technologies for using energy resources, MAEEITUER, consists of two basic components:

- model for analyzing environmental impacts of technologies for using energy resources – MAEITUER,
- model for evaluating environmental impacts of technologies for using energy resources – MEEITUER.

In concrete terms, the aim is to interconnect the two single phases, the analysis phase, and the assessment phase. In the analysis phase, by applying the method of determining air pollutant emissions and by knowing the technological process of generating electricity and thermal energy in thermal power stations, it is possible to calculate air pollutant emissions [3, 4]. The analysis stage is followed by the assessment stage, in which the values obtained from the analysis stage should be compared with the permissible limit values mentioned in relevant regulations or standards [3, 6, 12].

To succeed in carrying out assessments for situations lacking limit values, it is proposed to use a so-called dynamic assessment method [7, 14]. Such a dynamic assessment method is based on calculating pollutant emission gradients or environmental footprint gradients, which are established in the analysis stage as well as on the interpretation of calculated gradients, which can have positive and negative [14, 20]. In this way, it is possible to apply the MAEEITUER model to various single situations in the case of various thermal power plants, and after assessments appropriate conclusions can be drawn regarding the registered environmental impact of considered energy resource technologies as well as regarding appropriate measures needed to be taken [20].

2.3. ANALYTICAL PRESENTATION OF THE MODEL FOR ANALYZING AND EVALUATING THE ENVIRONMENTAL IMPACTS OF TECHNOLOGIES FOR USING ENERGY RESOURCES, MAEEITUER

The model integrates two basic parts as shown in Fig. 1. To develop each part as a component of the MAEEITUER model, specific tools to address each stage are used and applied. Thus:

• To carry out an in-depth analysis of the environmental impact of energy resource usage technologies, various mathematical tools are applied to determine the emissions of various pollutants resulting from the application of various energy resource usage technologies for electricity and thermal energy generation.

• To carry out an in-depth assessment of the environmental impact of energy resource usage technologies, various mathematical tools are applied in the form of the gradient method, which enables comparisons among different situations characterized by positive or negative gradients of pollutant emissions.

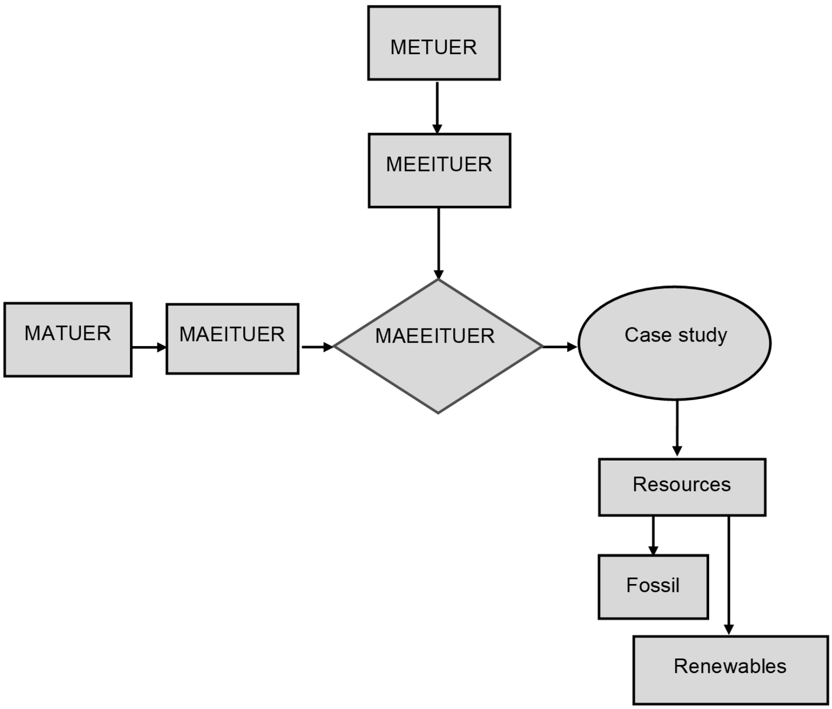

Fig. 1. Model for analyzing and evaluating environmental impacts of technologies for using energy resources [20]: MATUER – the model to analyze technologies for using energy resources, MAEITUER – the model for analyzing the environmental impacts of technologies for using energy resources, METUER – the model for evaluating technologies for using energy resources, MEEITUER – the model for evaluating the environmental impacts of technologies for using energy resources, MAEEITUER – the model for analyzing and evaluating the environmental impacts of technologies for using energy resources

To be able to apply these models, it is necessary to know emissions from the polluting source, which means that there is a need for a comprehensive database. In the present case, the polluting source is represented by the thermal power plants of Oltenia Energy Complex (OEC) that operate based on the combustion of fossil fuels, specifically lignite.

Needed data to apply the designed model, MAEEITUER has been acquired according to presented detailed information on the OEC official website https://www.ceoltenia.ro [21].

2.4. CASE STUDY. APPLYING THE MAEEITUER MODEL FOR CO_2 EMISSIONS RELATED TO OLTENIA ENERGY COMPLEX

In the case of complex combustion processes in thermal power plants, CO_2 emissions are calculated following the specific legislation and taking into account emission sources, i.e., a distinctly identifiable part of an installation or process within an installation emitting CO_2 emissions [22]. Thus, will be analyzed CO_2 emissions generated in the combustion process of raw materials used in combustion boilers, E_{CO_2B}, as well as CO_2 emissions generated by wet desulphurization of flue gases, flue gas discharge (FGD), E_{CO_2FGD}.

In this condition, the total emission CO_2, E_{CO_2tot}, generated in the plant, i.e., with the combustion process in the boiler and in the wet gas desulphurisation process is:

$$E_{CO_2\,tot} = E_{CO_2\,B} + E_{CO_2\,FGD} \tag{1}$$

During these industrial processes with significant CO_2 emissions, the account will be taken of so-called calculation factors, which means the net calorific value of the fuels used, emission factor, oxidation factor, conversion factor, and carbon content [22].

Based on the amount of fuel used for energy generation (coal, heavy-fuel oil, natural gas), the heating value of each fuel, the emission factor, and the oxidation factor, total CO_2 emissions can be calculated resulting from the combustion of the raw materials, i.e., coal, heavy-fuel oil, and gas in the boilers, as well as the CO_2 emissions from the simultaneous desulfurization of the gases.

Considering the analytical model for calculating the CO_2 emissions for a certain time interval, there is a need for concrete data from energy production processes in the context of OEC for the considered time interval. In this context, Table 1 shows CO_2 emissions taking into account the consumption of raw materials necessary to produce electricity at Oltenia Energy Complex during the period 2015–2022 [21].

Table 1

CO_2 emissions resulting from the consumption of raw materials during the period 2015–2022 [21]

Raw material	Year							
	2015	2016	2017	2018	2019	2020	2021	2022
Coal, mln t	20.61	19.22	21.89	21.53	19.32	13.29	15.93	14.51
Natural gas, mln Nm^3	34.26	23.26	31.12	21.33	25.73	25.05	28.77	14.81
Heavy-fuel oil, t	1863.7	1565.54	3480.38	3810	2285	1094	1205.39	1437.56
Limestone, t	–	401351	501508	511485	451537	322504	389026	341073
CO_2 emission, Mio t	13.717	12.685	13.860	13.055	11.012	7.156	8.268	7.955

2.5. CO_2 EMISSIONS ASSESSMENT MODEL

As already highlighted, various mathematical tools can be applied to make a thorough assessment of the environmental impacts of energy resource usage technologies. Those based on comparisons with permissible limit values of pollutant concentrations in various polluted environments are not applicable in this case concerning the environmental impact due to emissions of various pollutants into the air, water, or soil, as there are, at least so far, no legislated maximum permissible values for all emissions of various pollutants, such as CO_2 emissions.

For these reasons, the model proposed for the assessment of pollutant emissions within the MAEEITUER model is based on the method of determining different gradients of pollutant emissions. This approach allows comparisons among different situations characterized by positive or negative gradients of pollutant emissions, which occur because of applying various energy resource usage technologies for electricity and thermal energy generation.

Based on pollutant emission for a considered year of the assessment $E_{\mathrm{py}\,i}$ and pollutant emission for the previous year, $\mathrm{E}_{\mathrm{py}\,i-1}$, the gradient of the pollutant emission, ∇E_{p}, can be determined with the relation:

$$\nabla E_{\mathrm{p}} = E_{\mathrm{py}i} - E_{\mathrm{py}i-1} \tag{2}$$

where ∇E_{p} is the pollutant emission gradient over the considered time interval, kg, $E_{\mathrm{py}\,i}$ is the pollutant emission for a considered year, kg, and $E_{\mathrm{py}\,i-1}$ is the pollutant emission for a previous year, kg.

The results of the calculation based on Eq. (2) provide useful information to characterize the effects of measures established to reduce environmental impact when operating corresponding energy resource usage technologies.

Case 1. If calculated gradients are negative, i.e., $\nabla E_{\mathrm{p}} < 0$, a reduction in pollutant emissions from year to year occurs, thus being a desirable situation, which followed after implementing various measures to reduce the environmental impact of energy resources usage technologies.

Case 2. If calculated gradients have positive values, i.e., $\nabla E_{\mathrm{p}} > 0$, the pollutant emission increased from year to year, so implementing various measures to reduce the environmental impact of energy resources usage technologies did not have the expected effect. This calls for a rethinking of the whole process and corresponding measures in the operating phase of related energy resource usage technologies.

Case 3. If calculated gradients are equal to zero, i.e., $\nabla E_{\mathrm{p}} = 0$, the measures initially adopted do not affect the environmental impact of energy resource usage technologies. If, however, measures have been introduced to reduce the environmental impact, the result has not been as expected, which indicates unnecessary expenditure, i.e., a waste of money, which means that appropriate measures must be taken in the future to change this situation and to try reducing the environmental impact.

3. RESULTS AND DISCUSSION

The new-designed integrative MAEEITUER with its two main parts, a MAEITUER, and MEEITUER can be successfully applied for assessing different technologies already in the operation as well as for technologies in the designing or development phase. The model applied for analyzing environmental impacts of technologies for using energy resources, MAEITUER is based on several mathematical relations allowing exact calculations of single pollutants emissions in the environment, as it has been emphasized in the example of establishing corresponding CO_2 emissions.

Table 2

CO_2 emissions and footprint related to Oltenia Energy Complex for 2015–2022

Parameter	Year							
	2015	2016	2017	2018	2019	2020	2021	2022
E_{CO_2}, mln t	13.717	12.685	13.860	13.055	11.012	7.156	8.268	7.955
W_e, TWh	15.778	14.340	15.733	14.949	13.151	8.935	10.585	10.229
F_{CO_2}, t CO_2/MWh	0.869	0.885	0.881	0.873	0.837	0.801	0.781	0.777
∇E_{CO_2}, mln t		–1.032	1.175	–0.805	–2.043	–3.856	1.112	–0.313
∇F_{CO_2}, t CO_2/MWh		0.016	–0.004	–0.008	–0.036	–0.036	–0.020	–0.004

To succeed in assessing the potential environmental impact of operating coal-based power plants presented in the case study, the gradient-based dynamic assessment method will be applied. Based on CO_2 emissions for Oltenia Energy Complex (Table 1), as well as the electricity generated by OEC in the period 2015–2022, it is possible to determine the CO_2 footprint for the mentioned period, data being highlighted in Table 2. Thus, the CO_2 footprint F_{CO_2} is defined by the ratio between CO_2 emission and produced electricity:

$$F_{CO_2} = \frac{E_{CO_2}}{W_e} \tag{3}$$

where E_{CO_2} represents CO_2 emission, t CO_2, and W_e is produced electricity, MWh.

After applying the gradient-based dynamic assessment method (Table 2), the variation of the CO_2 emissions gradients during 2015–2022 at Oltenia Energy Complex have been calculated (Fig. 2). Determined by the gradient-based dynamic assessment method for CO_2 footprint, the CO_2 footprint gradients during 2015–2022 at Oltenia Energy Complex are presented in Fig. 3.

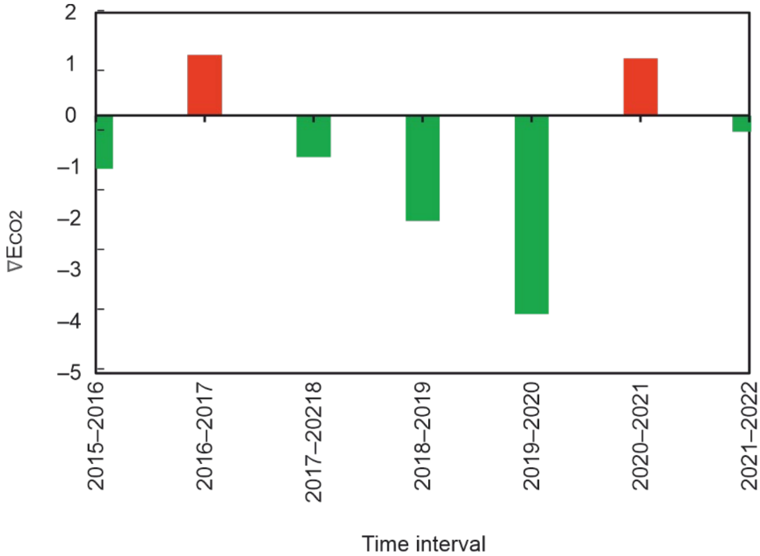

Fig. 2. Variation of the CO_2 emissions gradient during 2015–2022

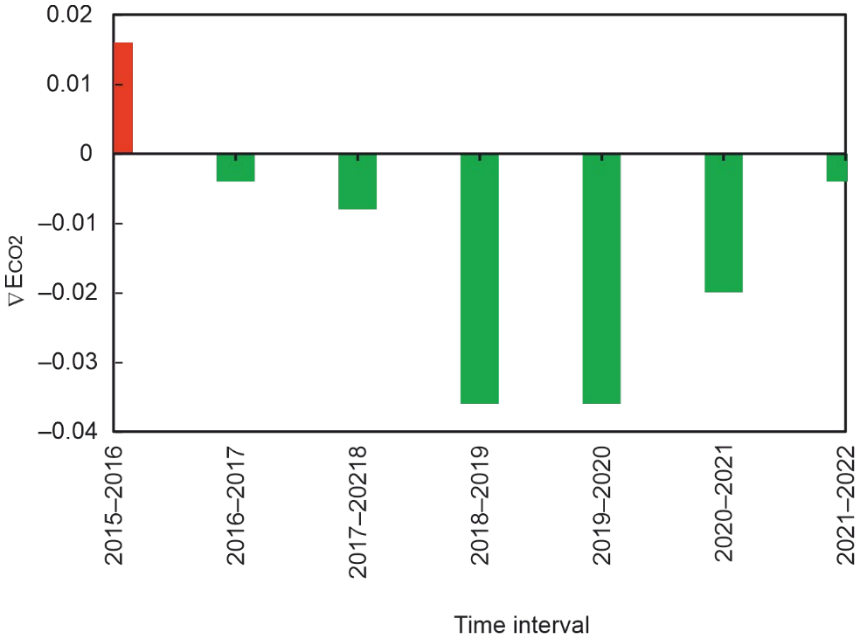

Fig. 3. Variation of the CO_2 footprint gradient during 2015–2022

- During the analyzed period, CO_2 emissions decreased from one year to another, the trend being negative. Nevertheless, there are two exceptions, where these emissions increased compared to previous years.

• In five cases, the CO_2 emissions gradient is negative, $\nabla E_{CO_2} < 0$. It follows that CO_2 emissions decreased and therefore the environmental impact decreased in the years 2015–2020 and 2021–2022, which means that applied technological and operational measures had a positive impact in terms of environmental protection.

• In two cases, the CO_2 emissions gradient is positive, $\nabla E_{CO_2} > 0$. CO_2 emissions and therefore the environmental impact increased in the years 2016–2017 and 2020 –2021, following that additional measures are necessary to be applied for its reduction.

• In the case of the CO_2 footprint, during the analyzed period it has an encouraging trend, recording negative values in six of the seven situations, which represents a continuous improvement, and a decrease in the negative impact on the environment related to electricity production.

• In six cases, the CO_2 footprint gradient is negative, $\nabla F_{CO_2} < 0$. The environmental footprint corresponding to energy production decreased, which means that the technological infrastructure for electricity generation has been used efficiently.

• In one case, the CO_2 footprint gradient is positive, $\nabla F_{CO_2} > 0$. The ecological footprint corresponding to energy production has increased, which means that the technological infrastructure for electricity generation has not been used efficiently.

By applying the MEEITUER based on the dynamic assessment method, the following cases regarding operating technological applications and their potential environmental impact can occur:

Case 1. $\nabla E_{CO_2} < 0$ and $\nabla F_{CO_2} > 0$ mean a decrease in CO_2 emissions, but the environmental impact emphasized by the CO_2 footprint related to produced electricity increased. Plants related to electricity generation require constructive and functional improvements to succeed in mitigating the environmental footprint and by this the overall environmental impact of considered technological application.

Case 2. $\nabla E_{CO_2} > 0$ and $\nabla F_{CO_2} < 0$ mean an increase in CO_2 emissions, but the installations used in the technological process were used efficiently, and the environmental impact relative to energy production decreased.

Case 3. $\nabla E_{CO_2} > 0$ and $\nabla F_{CO_2} > 0$ display the worst-case scenario, pollutant emissions and thus environmental impact increased, appropriate measures need to be taken to reduce pollutant emissions and/or to use available infrastructure more efficiently.

Case 4. $\nabla E_{CO_2} < 0$ and $\nabla F_{CO_2} < 0$ correspond to a decrease in CO_2 emission and environmental impact from related pollution due to energy production. This is the most favorable case.

Some models for analyzing and assessing the environmental impacts of various human economic activities have been developed over the years: WOLRD3 developed by the Club of Rome [10], International Futures, IFs [19], EPR [3] or EFENIA [11]. Even if these models integrate certain approaches for analyzing environmental impacts, these are generally not connected to certain assessment processes of considered technological applications. In contrast to these models, this aspect of assessment is included in the

MAEEITUER model presented in this article, besides the phase of analyzing environmental impacts, by the model MAEITUER. By this assessing the environmental impact of certain technologies is possible, even in the absence of admissible limit values published in various laws and implemented regulations, which generally refer to pollutant immissions, not to pollutant emissions. The gradient-based dynamic assessment method is based on the interpretation of determined gradients which can be negative, positive, or zero. This is to be understood as a new approach that allows assessing certain processes or phenomena even in the absence of admissible limit values.

4. CONCLUSION

Various models for analyzing and assessing the environmental impacts of various economic activities are currently under discussion for successful use in a harmonized way in different countries at a global level, thus allowing comparisons to be made among different analyzed situations. A MAEEITUER presented in this article demonstrates its potential in recognizing dangerous trends regarding environmental impacts in operating different technological applications. The model offers possibilities for future use in the analysis and assessment of environmental impacts of various technological applications by its two component models, one for analysis, MAEITUER, and the other one for evaluating environmental impacts of technological applications, MEEITUER. It is to be mentioned that the MAEEITUER allows analysis and assessment of the potential environmental impact of various technological processes even before they are carried out, i.e., at the initial design stage. This fact enables a prior approach and a better understanding of potential undesirable negative effects of designing and using certain technological applications, not just in the energy sector.

By calculating gradients of CO_2 emissions, ∇E_{CO_2}, generated by operating various technologies that use energy resources for electricity and heat production but also establishing the gradients of CO_2 footprint, ∇F_{CO_2}, for thermal power plants within Oltenia Energy Complex, interpretations can be made, and useful conclusions can be drawn regarding their operating mode, and the use of related infrastructure, but also conclusions related to potential environmental impact. Thus, it has been emphasized that in some cases the gradient of CO_2 emissions was negative, but the gradient of the CO_2 footprint was positive, which means that by using the related infrastructure as well as by taking appropriate technical-organizational measures, CO_2 emissions were reduced (perhaps also because less electricity was produced, consequently consuming less coal by burning). However, if the gradient of the CO_2 footprint is simultaneously positive, it follows that the environmental impact related to generated electricity has increased. It highlights the fact that the use of specific plants for electricity generation requires constructive and functional improvements to succeed in producing electricity without simultaneously recording a positive gradient of environmental footprint. When the CO_2

emission gradient is positive, but the footprint gradient is negative, it follows that although CO_2 emission increased, energy production plants have been used more efficiently, and the environmental impact of electricity generation decreases. If the CO_2 emission gradient is negative and the footprint gradient is also negative, it means that the CO_2 emission decreased and the environmental impact through related pollution due to energy production also decreased, this being practically the most favorable case and therefore desirable to be always obtained when generating electricity in thermal power plants based on fossil fuels combustion.

In the context of the currently much debated European Green Deal future usage odds of energy resources must be developed by considering such integrative models as the one presented in this article, MAEIMTURE, for analyzing and assessing environmental impacts of energy resource usage technologies. In the future diverse energy resources must be considered and their usage odds have to be assessed by establishing especially environmental footprints because of their use to assure sustainable energy production and consumption.

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