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LIFE CYCLE IMPACT ASSESSMENT OF FOSSIL FUELS

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The main objective of this study is to compare the life cycle of fossil fuel (coal, natural gas and oil) in order to assess the overall environmental impact. In this respect it was analyzed the fossil fuels energy production based on the best available energy technologies for each fuel. The methodology used in order to evaluate the total environmental impact was Life Cycle Analysis.

The method allowed on one side the identification of the pollutants generated in each stage: extraction, treatment, transportation and combustion, and on the other side identification of the main classes of impact according the pollutants inventory.

Keywords: LCA, fossil fuels, multi-criteria analysis.

1. Introduction

According to estimates the International Energy Agency (IEA), centralized in the annual World Energy Outlook, fossil fuels will account for 84 % growth in energy demand in the period 2005-2030. Reflecting this trend, the share of coal in global energy demand will increase from 25% to 28%. Natural gas, a fuel with a much lower level of pollution than coal, will register a moderate growth increase in use worldwide, from 21% to 22%, while nuclear power, which doesn't generate carbon dioxide emissions, will be used in a lesser extent, representing 5% of global demand, comparing to 6 % at the 2005. Although global medium term, the share of coal in electricity production increases, in Romania it lasts the same amount as in the year 2007. Unlike coal, it seems that, at least in Romania, natural gas demand will grow in the near future. The opposite is oil whose request for the production of electricity will drop in coming years.

The life cycle assessment (LCA) is a tool utilized for evaluating the environmental impact on the assembly of activities associated with a product, service, process or production chain, starting from the raw material extraction up to the last waste elimination [1].

According to the data presented in table 1, the share of fossil fuels will continue to be high in 2020, as well. The absolute value for coal will increase, that

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of natural gas will remain practically constant, while oil energy will register a major decrease.

Table 1

Production of electrical energy in 2007 and electrical energy production forecast at the level of the year 2020 [2]

Indicators	2007 achieved		2020 forecast	
m.u.	TWh	%	TWh	%
Electrical energy production of which:	61.68	100	100	100
Total thermal, of which:	38	61.6	45.9	45.9
- Coal	20.86	54.9	34.9	76.0
- Natural gas	9.61	25.3	9.5	20.7
- Oil	7.53	19.8	1.5	3.3
Hydro	15.97	25.9	32.5	32.5
Nuclear	7.71	12.5	21.6	21.6

2. Life cycle of fossil fuels

The analyzed chains of electrical energy production are the following: the coal, natural gas and oil life cycle.

For the analyzed chains, the following analysis stages have been considered: extraction, treatment, transport and combustion [3].

Within the analysis the following study hypotheses have been formulated:

❖ The electrical energy production solutions by each type of fuel have been:
  - For coal, a technical solution consisting of circulating fluidized bed combustion with supercritical parameters + combined cycle power plant, with 40 % efficiency has been chosen. The coal utilized is hard coal. As a result of the calculations based on the chosen coal composition, there resulted a low heating value of 27,000 [kJ/kg].
  - For natural gas, the technical solution of the gas-steam combined cycle with 55% efficiency has been selected. The gas that was used had a low heating value of 50,000 [kJ/kg].
  - For oil, the technology considered for producing energy is boiler combustion at atmospheric pressure + steam turbine. The low heating value used in this paper is 43 100 kJ/kg. The efficiency considered for the electrical energy production along this chain is 45 % [4].

❖ Own energy consumption during the different life cycle stages is covered on the basis of the respective fuel by each chain.

❖ The energy solutions used have not been equipped with flue gas treatment equipment not to disadvantage a certain energy chain.

❖ The considered efficiencies for each life cycle stage have been [3,4]:
  - For coal (co): extraction (η_{ex}=75%), treatment (η_{tr}=95%), transport (η_{tp}=85%), combustion (η_{cb}=40%);

- For natural gas (ng): extraction (η_{ex}=90%), treatment (η_{tr}=95%), transport (η_{tp}=90%), combustion (η_{cb}=55%) ;
- For oil (o) : extraction (η_{ex}=90%), treatment (η_{tr}=95%), transport (η_{tp}=90%), combustion (η_{cb}=45 %).

These values were used in the LCA methodology, but their interpretation must be done with caution.

❖ The average transport distance that has been considered in the case of natural gas and oil was 450 km, and in the case of coal, 100 km, respectively.

Figure 1 presents the field of study for each chain.

After establishing the 1 TWh functional unit and the efficiencies of the stages, starting from the low heating value of each fuel, the necessary amount of fuel has been calculated by each stage and functional unit (FU). The reference unit (RU) in this study represents the amount of fuel necessary during each stage for producing 1 TWh of electrical energy. The emissions generated by the functional unit have been updated at the functional unit with the equation 1.

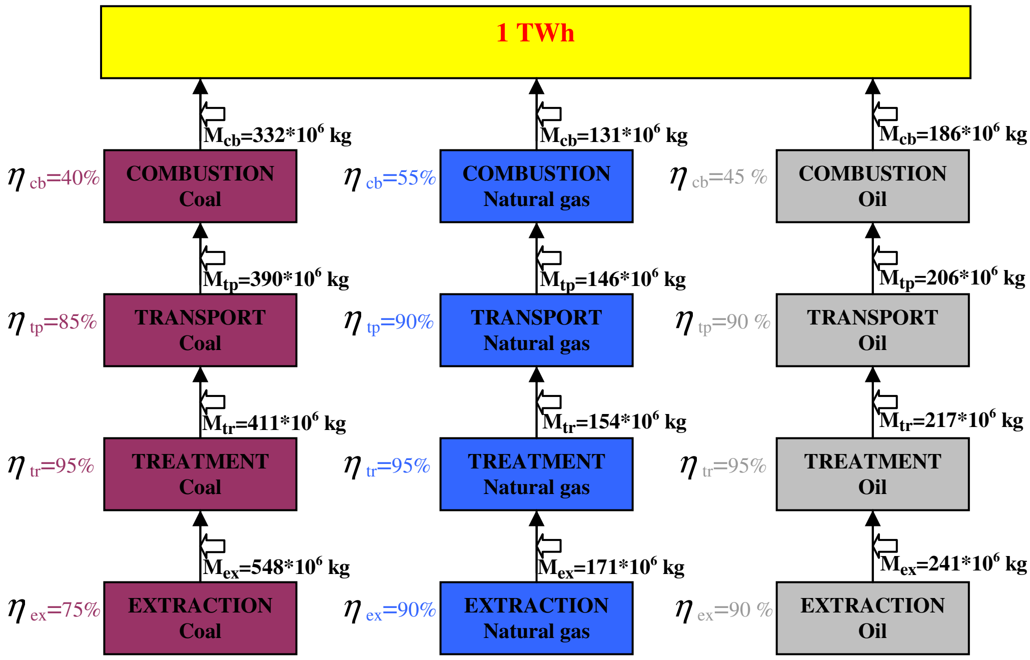

Fig.1. Field of study for each chain.

$$E_r = E_i * RU, \quad \text{[g/TWh]}. \tag{1}$$

Where:

E_r – recalculated pollutant emission by functional unit;

E_i – initial emissions collected during the inventory stage, in g/kg of fuel;

RU - reference unit specific to each life cycle stage, in kg fuel / TWh.

Within the inventory analysis, data on the generated environmental polluting emissions by each life cycle stage have been gathered, and on the basis of the inventoried pollutants, the classes have been identified.

3. Results of the analyzed chain inventory analysis

The following observations can be made on the emissions generated over the coal chain (table 2) during the entire life cycle [5]:

- From the quantitative point of view, the generated air emissions exceed by far the emissions polluting the water and soil ecosystems. The main pollutants generated over the coal life cycle are: CO_2=816,097 t/FU, dust particles under 10 μm (PM_{10}=7,364 t/FU), SO_2=5,360 t/FU, NO_2=2,680 t/FU and CH_4=730 t/FU. Although the other pollutant values are insignificant, it is nevertheless necessary to develop the impact analysis for determining their environmental impact.
- As concerns the share of pollutants by each stage of the life cycle, the following aspects should be mentioned:
  - *Carbon dioxide*: of the total emissions, during the combustion stage, approx. 794 kt/FU have been generated, representing about 97%. The next stage from point of view of its share is transport, generating about 14 kt/UF, representing approximately 2% of the total CO_2 emissions. During the treatment and extraction stage, the share of CO_2 emissions within the total emissions is 0.4%, and 0.6%, respectively.
  - *Dust* has been almost entirely generated (99.7%) during the combustion stage.
  - *Sulfur dioxide*: during the combustion stage approximately 5.2 kt/FU representing about 97% of the total SO_2 emissions, have been generated. During the transport stage about 1.5% is generated, while the share of SO_2 emissions does not surpass 1% during the extraction and treatment stages.
  - *Nitrogen dioxide*: As for the other pollutants, the combustion stage generates the highest share of NO_x emissions, about 93%. During the other stages the shares are insignificant, except for the transport stage when the percentage of NO_x emissions generated is 5.5%.
  - *Methane*: In comparison with other pollutants, in the case of methane the extraction stage generates the highest amount of about 60%, followed by the treatment stage generating 40%. The combustion and transport stages have insignificant emission methane values.
- As in the case of the coal chain, the natural gas chain (table 3) registers the highest values of emissions in the air ecosystem [6]. The main pollutants generated over the natural gas life cycle are: carbon dioxide (CO_2=437,909

t/FU), methane (CH_4=3,740 t/FU), nitrogen dioxide (NO_2=561 t/FU), carbon monoxide (CO=283 t/FU), sulfur dioxide (SO_2=275 t/FU);

❖ Relating to the share of pollutants within each stage of the life cycle the following aspects are worth-mentioning:
  - *Carbon dioxide*: of the total emissions, approximately 371 kt/FU are generated during the combustion stage, representing about 85%. The stages that follow, from the point of view of their share, are the extraction share generating 9% and the treatment stage with 6%. The transport stage has insignificant values of CO_2 emissions.
  - *Methane:* is mainly generated during the extraction, 1,664 t/FU (44.5%), treatment 1,111 t/FU (29.7%) and transport 920 (24.6%) stages, the methane emissions generated during the combustion stage being insignificant.
  - For *nitrogen dioxide*, the shares are the following: extraction (49.7%), treatment (33.2%), combustion (16.9%), the transport stage being the least polluting.
  - *Carbon monoxide*: the stage that has the highest share relating to CO emissions is extraction (54%), followed by the treatment stage (36%). The combustion and transport stages have the following shares: 9.5% and 0.5%, respectively.
  - As concerns *sulfur dioxide,* the extraction and treatment stages are mainly responsible for generating this pollutant amounting to 59.4% and 39.7%, respectively. During the combustion stage, SO_2 emissions do not surpass 1% of the total SO_2 emissions.

❖ In the case of oil life cycle, table 4 presents the highest values of emissions in the air ecosystem [6]. The main pollutants generated over the oil chain are: carbon dioxide (CO_2=919,000 t/FU), methane (CH_4=163 t/FU), nitrogen dioxide (NO_2=940 t/FU), carbon monoxide (CO=610 t/FU), sulfur dioxide (SO_2=1,700 t/FU) and dust 104 t/FU;

❖ Relating to the share of pollutants within each stage of the life cycle the following aspects are worth-mentioning:
  - *Carbon dioxide*: of the total emissions, about 860 kt/FU are generated during the combustion stage, representing about 93%. The stages that follow, from the point of view of their share, are the extraction and treatment with about 3 %. The transport stage has insignificant values of CO_2 emissions.
  - *Methane:* is mainly generated during the extraction, 91 t/FU (55.5%), and combustion stage 35 t/FU (21 %). In the treatment and transport stage the methane emissions are 19 t/FU (12 %).

Table 2

Pollutants corresponding to the coal life cycle (t/FU)

Coal	Extraction	Treatment	Transport	Combustion	Total
Air					
CO_2	4,570.22	3,101.67	14,036.86	794,388.26	816,097.01
CO	5.4	3.6	101	156	266
SO_2	34.31	22.52	76.12	5,227.69	5,360.64
NH_3	59	39	0.1	0.1	98.2
CH_4	433.92	289.10	0.73	6.79	730.54
NO_2	22.78	15.28	147.69	2,494.30	2,680.05
N_2O	0.6	0.4	0.2	3.2	4.4
Dust (PM_{10})	5.90	0.51	14.74	7,343.82	7,364.96
Mercury	0	0	0	0.037	0.037
Molybdenum	0	0	0	0.038	0.038
Nickel	0	0	0	0.060	0.060
Water					
Phenol	3.01E-06	2.007E-06	6.67E-10	1.9143E-05	2.42E-05
NH_4	10	6.7	0	0	16.7
COD	0.685	0.457	0	0.066	1.208
Agricultural soil					
Barium	0	0	0	0.437	0.437
Copper	0	0	0	0.114	0.114
Nickel	0	0	0	0.156	0.156
Vanadium	0	0	0	0.317	0.317

Table 3

Pollutants corresponding to the natural gas life cycle(t/FU)

Natural gas	Extraction	Treatment	Transport	Combustion	Total
Air					
CO_2	39,596	26,402	440	371,471	437,909
NO	12	7.7	14	8.7	42.4
CO	153	102	1.4	27	283.4
SO_2	163	109	0.648	1.9	274.5
NH_3	0	0	0.336	21	21.3
CH_4	1,664	1,111	920	45	3,740
NO_2	279	186	0.570	95	560.6
N_2O	0.345	0.231	0.004	0	0.580
Dust (PM_{10})	13	8.2	0	62	83.2
Formaldehyde (CH_2O)	0	0	0	8.6	8.6
Water					
DCO	14	55	0	0	69
Phenyl chloride	0	0	0	0.005	0.005

- For *nitrogen dioxide*, the shares are the following: extraction (8 %), treatment (4 %), combustion (87 %), the transport stage being the least polluting.

- *Carbon monoxide*: the stage that has the highest share relating to CO emissions is combustion (44%), followed by the extraction stage (32 %). The treatment and transport stages have the following shares: 19 % and 6 %, respectively.
- As concerns *sulfur dioxide,* the combustion stage is mainly responsible for generating this pollutant amounting to 71 %. The extraction and transport stage presents 13 % and 10 % respectively. During the treatment stage, SO_2 emissions do not surpass 6 % of the total SO_2 emissions.

Table 4

Pollutants corresponding to the oil life cycle(t/FU)

Oil	Extraction	Treatment	Transport	Combustion	Total
Air					
CO_2	30,301	28,399	2,200	858,070	918,970
NO	16	9.65	3	87	115.65
CO	192.70	116	34.7	266.9	610.3
SO_2	224.01	91.9	176.83	1207.1	1,699.84
NH_3	0	0	7.52	206.24	213.76
CH_4	90.91	18.30	19.4	35.12	163.73
NO_2	74.60	37.60	13.84	814.07	940.11
N_2O	0.80	0.5	0.4	23	24.7
Dust (PM_{10})	13.50	3.4	0	88	104.9
Formaldehyde (CH_2O)	0	0	0	18.57148572	18.571
Water					
DCO	18.84	77.7	0	0	96.54
Phenyl chloride	0	0	0	0.007	0.007
Agricultural soil					
Lead	0.05	3.92	0.028	0.00017	3.998

4. Impact analysis

Based on the pollutants inventoried during the inventory analysis, the following impact classes have been identified: ADP – Abiotic depletion potential, GWP – Global warming potential, AP – Acidification potential, POCP – Photochemical ozone creation potential, EP-Eutrophication, HTP – Human Toxicity Potential, FAETP – Freshwater aquatic ecotoxicity potential, MAETP – Marine aquatic ecotoxicity potential, TETP- Terrestrial ecotoxicity potential [7].

The impact indicators have been calculated by means of the relationships given in table 5. The legend is given below the table.

Tables 6, 7 and 8 present a comparison between the impact indicators separately calculated for each stage of the life cycle (coal, natural gas and oil) and by the overall life cycle.

Table 5

Quantification of impact indicators [7, 8]

Impact class	Pollutants	Calculation relationship	Used notations and values
“Abiotic depletion potential” [kg antimony eq./kg emission]	-	$ADP = \sum_i ADP_i * m_i$	ADP_{oil}=0,0201 $ADP_{natural\ gas}$=0,0187 ADP_{coal}=0,0134
“Global warming potential” [kg CO_2 eq. /kg emmission]	CO_2, CH_4, N_2O	$GWP = \sum_i GWP_i * m_i$	GWP_{CO2}=1 GWP_{CH4}=21 GWP_{N2O}=310
“Acidification potential” [kg SO_2 eq./kg emmission]	SO_2, NH_3, NO_2	$AP = \sum_i AP_i * m_i$	AP_{SO2}=1,2 AP_{NH3}=1,6 AP_{NO2}=0,5
“Photochemical ozone creation potential” [kg ethene eq./kg emmission]	CO, SO_2, CH_4, CH_2O, NO_2	$POCP = \sum_i POCP_i * m_i$	$POCP_{CO}$=0,027 $POCP_{SO2}$=0,048 $POCP_{CH4}$=0,006 $POCP_{CH2O}$=0,519 $POCP_{NO2}$=0,028
“Eutrophication potential” [kg phosfate eq./kg emmission]	NO, NH_3, NO_2, COD, NH_4	$EP = \sum_i EP_i * m_i$	EP_{NO}=0,200 EP_{NH3}=0,350 EP_{NO2}=0,130 EP_{COD}=0,022 EP_{NH4}=0,350
“Human toxicity potential” [kg 1,4 dichlorbenzene eq./kg emmission]	SO_2, NH_3, NO_2, Praf, CH_2O, Pb, Fenol, HCl, HF etc	$HTP = \sum_i \sum_{com} HTP_{com,i} * m_{com,i}$	HTP_{SO2}=0,096 HTP_{NH3}=0,100 HTP_{NO2}=1,200 HTP_{Praf}=0,820 HTP_{CH2O}=0,830 HTP_{Pb}=3300 HTP_{Fenol}=0,520 HTP_{HCl}=0,500 HTP_{HF}=94
“Freshwater aquatic ecotoxicity potential” [kg 1,4 dichlorbenzene eq./kg emmission]	CH_2O, Pb, Fenol, HF etc	$FAETP = \sum_i \sum_{com} FAETP_{com,i} * m_{com,i}$	$FAETP_{CH2O}$=8,3 $FAETP_{pb}$=6,5 $FAETP_{Fenol}$=1,5 $FAETP_{HF}$=4,6
“Marine aquatic ecotoxicity potential” [kg 1,4 dichlorbenzene eq./kg emmission]	CH_2O, Pb, Fenol, HF etc	$MAETP = \sum_i \sum_{com} MAETP_{com,i} * m_{com,i}$	$MAETP_{CH2O}$=1,6 $MAETP_{pb}$=750 $MAETP_{Fenol}$=0,056 $MAETP_{HF}$=52
“Terrestrial ecotoxicity potential” [kg 1,4 dichlorbenzene eq./kg emmission]	CH_2O, Pb, Fenol, HF etc	$TETP = \sum_i \sum_{com} TETP_{com,i} * m_{com,i}$	$TETP_{CH2O}$=0,940 $TETP_{Pb}$=33 $TETP_{HF}$=0,003

The legend:

AP_i – acidification potential of i substance emitted in the air;

$POCP_i$ – photochemical polluting potential of emitted i substance;

EP_i – eutrophication potential of emitted i substance;

$HTP_{icom,i}$– potential of human toxicity of i substance emitted in a certain compartment;

$FAETP_{icom,i}$– ecotoxicity potential on fresh water of a i substance emitted in a certain compartment;

$MAETP_{icom,i}$– ecotoxicity potential on salt water of i substance emitted in a certain compartment;

m_i – amount of i substance emitted in the respective compartment

$TETP_{icom,i}$– ecotoxicity potential on the terrestrial systems of i substance emitted in a certain compartment;

com=compartment (air, fresh water, salt water, agricultural soil, industrial soil);

$a_{com,i}$= amount of i substance emitted in the respective compartment [kBq]
m_i for ADP– quantity of resource i used;
m_i for GWP, AP, POCP, EP– amount of i substance emitted
m_i for HTP, FAETP, MAETP, TETP– amount of i substance emitted in the respective compartment

Table 6

Impact indicators for the coal chain

Impact indicators	Stages				
	Extraction	Treatment	Transport	Combustion	Total
ADP [t Sb eq.]	6,527	0	0	0	6,527
GWP [t CO_2 eq.]	17,288	11,588	17,638	994,045	1,040,558
AP [t SO_2 eq.]	161	106	207	9,400	9,873
POCP [t ethene eq.]	6	4	12	405	428
EP [t PO_4^{3-} eq.]	28	19	24	405	476
HTP [t 1,4 DCB eq.]	50	30	246	33,681	34,007
FAETP [t 1,4 DCB eq.]	0	0	0	680	680
MAETP [t 1,4 DCB eq.]	0	0	0	10,021	10,021
TETP [t 1,4 DCB eq.]	0	0	0	219	219

Table 7

Impact indicators for the natural gas chain

Impact indicators	Stages				
	Extraction	Treatment	Transport	Combustion	Total
ADP [t Sb eq.]	3,192	0	0	0	3,192
GWP [t CO_2 eq.]	74,639	49,809	19,765	372,418	516,631
AP [t SO_2 eq.]	335	223	2	83	643
POCP [t ethene eq.]	22	15	6	6	49
EP [t PO_4^{3-} eq.]	39	27	3	21	90
HTP [t 1,4 DCB eq.]	468	12,157	5	175	12,805
FAETP [t 1,4 DCB eq.]	0	22	0	71	93
MAETP [t 1,4 DCB eq.]	353	38,983	12	15	39,363
TETP [t 1,4 DCB eq.]	1	110	0	8	119

Based on the calculated impact indicators, a comparative analysis of the three energy chains by each impact class is presented.

On the basis of the results obtained for the impact analysis, the following conclusions can be drawn:

- ❖ From the point of view of the "depletion of natural resources (abiotic)" impact indicator, the coal chain has the highest value (6,527 t Sb eq.) against the value registered for the natural gas chain (3,192 t Sb eq.). The corresponding value of the oil chain is 4,848 t Sb eq..
- ❖ By analyzing the „human toxicity" impact indicator, we can draw the following conclusions: the coal chain has the highest value (approximately 34,000 t 1,4 DCB eq.) especially due to the pollutants generated during the combustion stage, such as arsenic (51%), dust (22%), NO_2 (12%) and nickel

(6%), the rest of pollutants representing less than 9%. As concerns the natural gas chain, HTP represents approximately 12,800 t 1,4 DCB eq., mainly due to the lead emissions in soil generated during the treatment stage (94%). The oil chain presents a value of 15,639 t 1,4 DCB eq. for the same indicator mainly due to the Pb emission (63%).

Table 8

Impact indicators for the oil chain

Impact indicators	Stages				
	Extraction	Treatment	Transport	Combustion	Total
ADP [t Sb eq.]	4,848	0	0	0	4,848
GWP [t CO_2 eq.]	32,459	28,938	137	865,937	927,471
AP [t SO_2 eq.]	306	129	12	2,186	2,633
POCP [t ethene eq.]	16.5	7.6	0.5	75	99.6
EP [t PO_4^{3-} eq.]	13	8.5	0.3	195	216.8
HTP [t 1,4 DCB eq.]	302	14,128	7	1,202	15,639
FAETP [t 1,4 DCB eq.]	0,4	25	0	154	179.4
MAETP [t 1,4 DCB eq.]	588	46,028	17	32	46,665
TETP [t 1,4 DCB eq.]	1.7	129	0	17	147.7

- Relating to the „acidification" indicator, the values obtained in this study are 10,200 t SO_2 eq. corresponding to the coal chain (the contribution of the SO_2 amounting to 80%) 640 t SO_2 eq. for the natural gas chain (the contribution of the SO_2 emission amounting to 51% and of the NO_x to 43%) and 2,633 t SO_2 eq. for the oil chain, the pollutants causing this impact category being SO_2 which contributes approximately 76% and NO_x having a 24% share within the total calculated value for this indicator.
- From the point of view of the „eutrophication" indicator, the life cycle of coal registers a value of 476 t phosphate eq., while natural gas presents a value of 90 t phosphate eq.. For the oil chain the registered value is 216,8 t phosphate eq., by far lower than in the other two cases. The main pollutant contributing to this impact class is NO_2 (NO_x), regardless of the utilized type of fuel; in the case of the coal chain its contribution rises to 92% mainly generated during the combustion stage; the nitrogen oxide contribution in the case of the natural gas chain is 81 % while the in the case of the oil chain it reaches approximately (including all the nitrogen compounds) 100 %.
- As concerns the „photochemical pollution" indicator, the values obtained in this study are 428 t ethene eq. for the coal chain (the SO_2 emission contributes 75%), 48 t ethene eq. for the natural gas chain (the CH_4 emission contributes 47%, SO_2 contributes 27% and CO contributes 16%) and 99,6 t ethene equivalent for the oil chain, the SO_2 emission contributing approximately 64% of the total value of this indicator.

- The „freshwater aquatic toxicity" indicator has the following values: for the coal chain 680 t 1,4 DCB eq. of which beryllium contributes 44%, selenium 23%, vanadium 15%; in the case of the natural gas chain 93 t 1,4 DCB eq. of which CH_2O mainly contributes 77%, while for oil 179,4 t 1,4 DCB eq. covered 100% by Pb.
- The „marine aquatic toxicity" indicator has the following values: for the coal chain 10,021 t 1,4 DCB eq. of which the main pollutants are vanadium contributing 32%, selenium 30%, mercury 10% and nickel 9,5%; in the case of the natural gas chain, the value is 39,363 t 1,4 DCB eq., of which lead contributes 100%, and in the case of the oil chain the value of this indicator is 46,665 t 1,4 DCB eq. of which Pb contribution is 100%.
- The „terrestrial eco-toxicity" indicator registers the following values: for the coal chain 219 t 1,4 DCB eq. with the following pollutant contributions: mercury 54%, vanadium 15%, beryllium 11% and selenium 7%; for the natural gas the value of the indicator is 119 t 1,4 DCB eq. within which lead contributes 93%, and for the oil chain the indicator value is 147.7 t 1,4 DCB eq.).

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