COMPARATIVE ANALYSIS OF COAL, NATURAL GAS AND NUCLEAR FUEL LIFE CYCLES BY CHAINS OF ELECTRICAL ENERGY PRODUCTION

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Obiectivul principal al articolului constă în compararea din punct de vedere al impactului global asupra mediului înconjurător a filierelor de producere a energiei electrice utilizând cărbunele, gazele naturale şi uraniul.

Pentru un studiu complet a celor trei filiere energetice, s-a utilizat analiza de inventar, analiza de impact şi analiza de sensibilitate. În felul acesta au fost identificaţi principalii poluanţi generaţi în cadrul fiecărei etape: extracţie, tratare, transport şi combustie respectiv a principalelor clase de impact reţinute pe baza poluanţilor inventariaţi. În cadrul analizei de sensibilitate, indicatorii de impact au fost grupaţi în trei clase, acestea fiind ponderate diferit.

În concluzie, filiera de uraniu este cea mai puţin poluantă. În schimb, filiera de cărbune prezintă un puternic impact asupra mediului înconjurător în special datorită lipsei echipamentelor de tratare a gazelor de ardere.

The main objective of the paper consists in comparing the chains of electrical energy production from coal, natural gases and uranium from the point of view of their environmental impact.

For a complete study of the three chains, inventory, impact, and sensitivity analyses have been used. Thus, the main pollutants generated during each stage: extraction, treatment, transport and combustion, the main impact classes based on the inventoried pollutants, respectively, have been identified. Within the sensitivity analysis, the impact indicators have been grouped into three classes, with different shares.

In conclusion, the uranium chain is the least pollutant, while the coal chain has a great environmental impact, especially due to the lack of flue gas treatment equipment.

Keywords: electrical energy, coal, natural gas, uranium, life cycle assessment (LCA)

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1. Introduction

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].

The analysis of the life cycle includes four stages:

- Definition of objectives, of the functional unity and of the field of study;
- The inventory analysis, including emission data gathering;
- The impact analysis, during which emissions are translated into potential impacts;
- Comparative assessment and interpretation of the results.

The paper represents the first stage of a more comprehensive study and aims at establishing an optimum scenario for covering Romania's electrical energy consumption in 2020, considering environmental impact.

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 of natural gas will remain practically constant, while nuclear energy will register a major increase [2].

Table 1

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

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	21.0
Hydro	15.97	25.9	32.5	32.5
Nuclear	7.71	12.5	21.6	21.6

2. Electrical energy production chains

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

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, with 45% 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 uranium the technology considered for producing nuclear energy at the Cernavoda Nuclear power plant, is based on the CANDU type nuclear reactor, operating on natural uranium from our country. The efficiency considered for the electrical energy production along this chain is 35.5% [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 utilized have not been equipped with flue gas treatment equipment not to disadvantage a certain energy chain.

❖ For uranium, non-radioactive emissions have been collected over the entire life cycle and not by each stage of the former. Radioactive emissions, on the contrary, have been collected by each life cycle stage (according to table 5).

❖ The considered efficiencies for each life cycle stage have been [3,5]:

- For coal (co): extraction (η_{ex}=75%), treatment (η_{tr}=95%), transport (η_{tp}=85%), combustion (η_{cb}=45%);
- For natural gas (ng): extraction (η_{ex}=90%), treatment (η_{tr}=95%), transport (η_{tp}=90%), combustion (η_{cb}=55%) ;
- For uranium (u) : extraction (η_{ex}=75%), treatment (η_{tr}=95%), transport (η_{tp}=85%), combustion (η_{cb}=35,5%).

These values serve as orientation.

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

The functional unit for the three chains is of 1 TWh.

Fig. 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 calculated by means of relationship 1.

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

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.

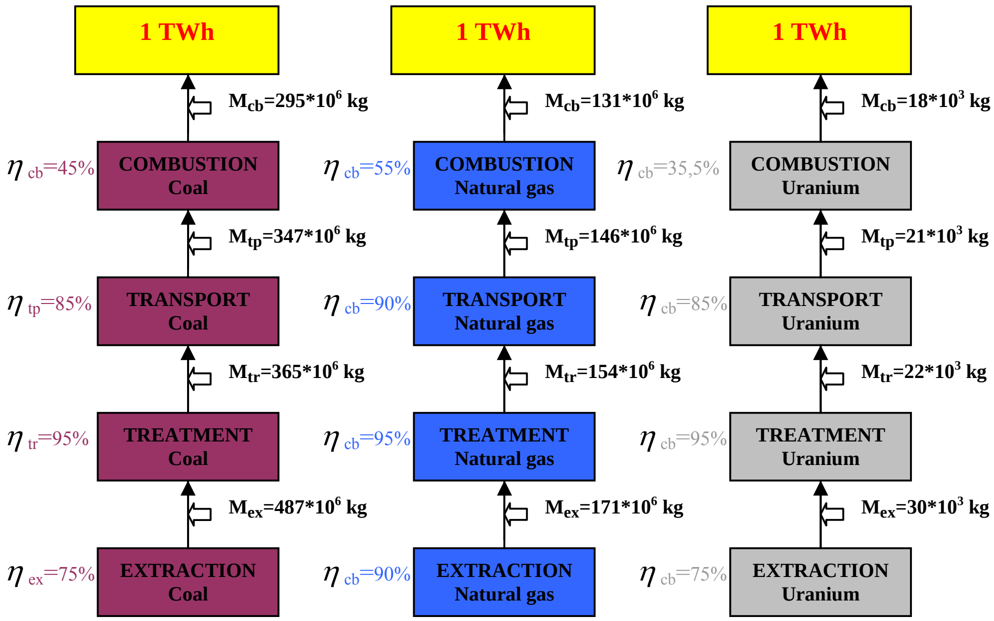


Fig.1. Field of study for each chain

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 [6]:

- ❖ 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=1,020,011 t/FU, dust particles (PM_{10}=9,205 t/FU), SO_2=6,699 t/FU, NO_2=3,350 t/FU and CH_4=912 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:
  - <u>*Carbon dioxide*</u>: of the total emissions, during the combustion stage, approx. 993 kt/FU have been generated, representing about 97%. The next stage from point of view of its share is transport, generating about 17 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 6.5 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 [7]. 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.

Table 2

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

Coal	Extraction	Treatment	Transport	Combustion	Total
Air					
CO_2	5,712	3,876	17,542	992,881	1,020,011
CO	5.4	3.6	101	156	266
SO_2	42	28	95	6,534	6,699
NH_3	59	39	0.1	0.1	98.2
CH_4	542	361	0.913	8.5	912
NO_2	28	19	185	3,118	3,350
N_2O	0.6	0.4	0.2	3.2	4.4
Dust (PM_{10})	7.4	0.6	18	9,179	9,205
Antimony	0	0	0	0.004	0.004
Arsenic	0	0	0	0.050	0.050
Barium	0	0	0	0.013	0.013
Beryllium	0	0	0	0.002	0.002
Cadmium	0	0	0	0.004	0.004
Chromium	0	0	0	0.059	0.059
Cobalt	0	0	0	0.007	0.007
Copper	0	0	0	0.023	0.023
Lead	0	0	0	0.030	0.030
Mercury	0	0	0	0.037	0.037
Molybdenum	0	0	0	0.038	0.038
Nickel	0	0	0	0.060	0.060
Selenium	0	0	0	0.406	0.406
Vanadium	0	0	0	0.088	0.088
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					
Antimony	0	0	0	0.015	0.015
Arsenic	0	0	0	0.130	0.130
Barium	0	0	0	0.437	0.437
Beryllium	0	0	0	0.014	0.014
Cadmium	0	0	0	0.010	0.010
Chrome	0	0	0	0.222	0.222
Cobalt	0	0	0	0.047	0.047
Copper	0	0	0	0.114	0.114
Lead	0	0	0	0.100	0.100
Mercury	0	0	0	0	0
Molybdenum	0	0	0	0.039	0.039
Nickel	0	0	0	0.156	0.156
Selenium	0	0	0	0.010	0.010
Vanadium	0	0	0	0.317	0.317

Tables 4 and 5 present the non-radioactive and radioactive emissions generated during the uranium life cycle.

Tabelul 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
Agricultural soil					
Lead	0.030	3.3	0.001	0	3.3

By analyzing the radioactive and non-radioactive emissions generated over the uranium chain, the following observations should be made:

- The radioactive and non-radioactive emissions have been concentrated over the entire uranium life cycle considering the stages (table 4 and 5). In order to simplify the analysis of the uranium chain, global emissions at the level of the life cycle have been compared;
- From the quantitative point of view, the main pollutants emitted during the uranium life cycle are: CO_2=18,700 t/FU, SO_2=40 t/UF, NO_2=30 t/FU and CH_4=10 t/FU. Nevertheless, from the point of view of the powerful environmental impact of the radioactive emissions, the development of an impact analysis has been considered necessary.
- Among the radioactive emissions, Rn-222 emission is considered the most important one from the quantitative point of view (75% of the total radioactive emissions generated during the life cycle). It is generated during uranium extraction (1.3%) and milling (73.7%) stages.

Table 4

Non-radioactive emissions corresponding to the uranium life cycle (t/FU) [8]

Uranium	Total
CO_2	18,700
CO	10
SO_2	40
NH_3	0.01
CH_4	10
NO_2	30
N_2O	0.5
Dust (PM_{10})	10
Hydrogen Chloride (HCl)	0.8
Hydrogen Fluoride (HF)	0.1

Tabelul 5

Radioactive emissions generated during the uranium life cycle in (TBq/FU) [9]

Radioactive emissions from the uranium life cycle	Extraction	Milling	Conversion	Fuel enriching	Fuel preparation	Electrical energy production	Re-processing	Total
H-3						0.079	0.024	0.103
C-14					1.8E-09	0.0073	0.038	0.045
Aerosols					1.3E-10	3.5E-07		3.5E-07
Noble gases					4.4E-10	1.5	381	382.5
I-129							2.7E-05	2.7E-05
I-131						9.5E-07	3.8E-07	1.33E-06
I-133							1.7E-07	1.7E-07
Rn-222	18.8	1,101.21						1,120
U-234			3.4E-07	1.7E-07				5.1E-07
U-235			1.5E-08	8.9E-09				2.39E-08
U-238			3.2E-07	1.3E-10				3.2E-07
Pu-238							5.4E-12	5.4E-12
Pu-239							1.2E-11	1.2E-11

Fig. 2 presents a comparison of the three chains studied from the point of view of the CO_2 emissions generated over the entire life cycle, thus pointing out that the ratio: coal /natural gas/uranium is 1/0.43/0.02.

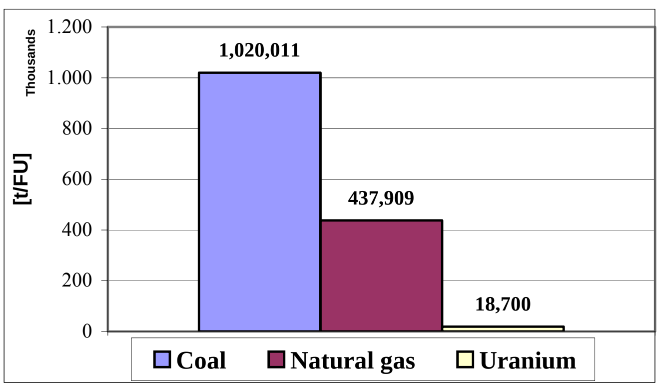


Fig. 2 Global CO_2 emissions corresponding to the three energy chains

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, IIR – Impacts of Ionizing radiation [10].

The impact indicators have been calculated by means of the relationships given in table 6. The legend is given below the table.

Table 6

Quantification of impact indicators

Impact class	Pollutants	Calculation relationship	Used notations and values
"Abiotic depletion potential" [kg antimony eq./kg emission]	-	$ADP = \sum_i ADP_i * m_i$	$ADP_{uranium}$=0,00287 $ADP_{natural\ gas}$=0,0187 $ADP_{lignite}$=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
"Impacts of ionising radiation" [year]	H-3,C-14, I-129, I-131, I-133, Rn-222, U-234, U-235, U-238, Pu-238, Pu-239	$IIR = \sum_{com} \sum_i FD_{com,i} * a_{com,i}$	U-234=9,7E-08(air) U-234=2,4E-09(fresh water) U-234=2,31E-11(salt water)

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;
$FD_{com,i}$= deterioration factor characterizing the i substance emitted in the respective compartment [an/kBq];
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

Tables 7, 8 and 9 present a comparison between the impact indicators separately calculated for each stage of the life cycle (coal, natural gas and uranium) and by the overall life cycle.

Table 10 presents the impact of ionizing radiations determined by the overall life cycle of uranium and by each stage separately. This indicator is specific to the uranium chain.

Table 7

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 8

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

Table 9

Impact indicators for the uranium chain

Impact indicators	Total
ADP [t Sb eq.]	0.086
GWP [t CO_2 eq.]	19,071
AP [t SO_2 eq.]	63
POCP [t ethene eq.]	3.1
EP [t PO_4^{3-} eq.]	3.9
HTP [t 1,4 DCB eq.]	57.6
FAETP [t 1,4 DCB eq.]	0.4
MAETP [t 1,4 DCB eq.]	5
TETP [t 1,4 DCB eq.]	0

Table 10

Assessment of the ionizing radiation impact corresponding to the uranium chain

Stages	IIR for air [year]	IIR for the underground water [year]	IIR for salt water [year]	Total IIR [year]
Extraction	0.451	0	0	0.451
Milling	26	0	0	26
Conversion	3.59E-05	1.59E-06	1.56E-08	3.75E-05
Fuel enriching	1.67E-05	4.29E-07	4.14E-09	1.71E-05
Fuel preparation	3.78E-07	0	2.16E-09	3.80E-07
Electrical energy production	1.534	3.60E-05	0.009	1.5
Reprocessing	8.0	1.10E-05	0.048	8.1
IIR uranium by environments [year]	36	4.90E-05	0.057	-
Total generated IIR uranium [year]	36			

Based on the calculated impact indicators, a comparative analysis of the three energy chains by each impact class is presented. At the same time, the following diagrams (Fig. 3) also present the pollutant contribution to the impact classes.

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 uranium chain is much lower, of only 0.086 t Sb eq.. This is mainly due to the inferior calorific power of the fuel and the utilization efficiency within each stage, respectively.

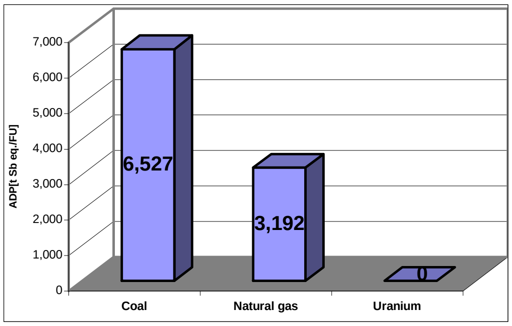


Fig. 3.1 Assessment of the energy chains by the ADP indicator.

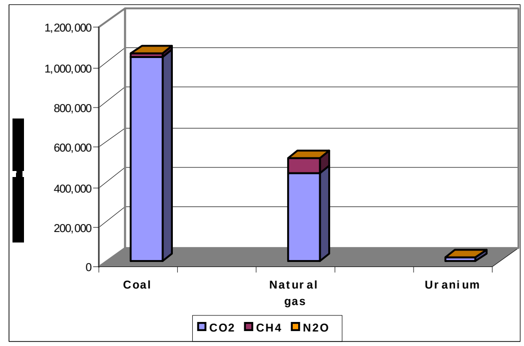


Fig. 3.2 Assessment of the energy chains by the GWP indicator.

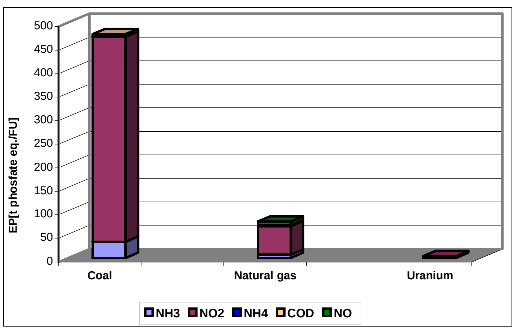


Fig. 3.3 Assessment of the energy chains by the EP indicator.

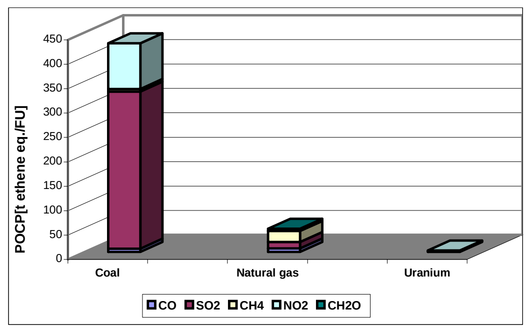


Fig. 3.4 Assessment of the energy chains by the POCP indicator.

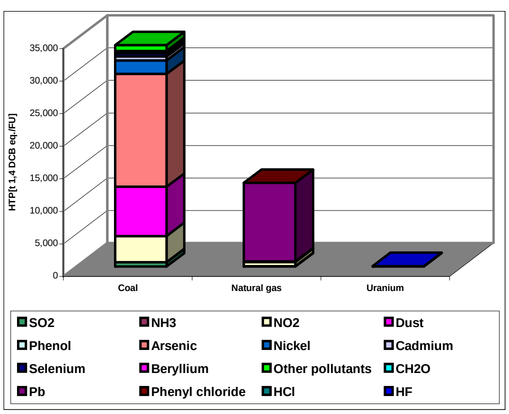


Fig. 3.5 Assessment of energy chains by the HTP indicator.

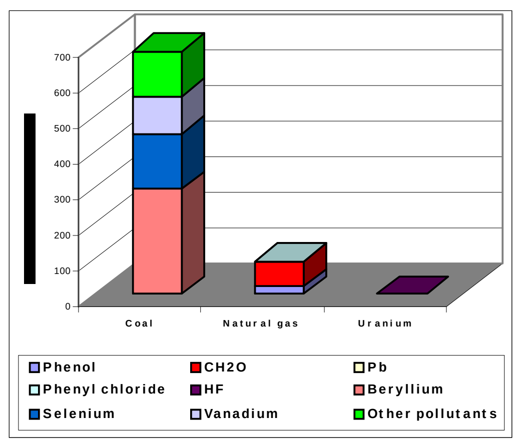


Fig. 3.6 Assessment of energy chains by the FAETP indicator.

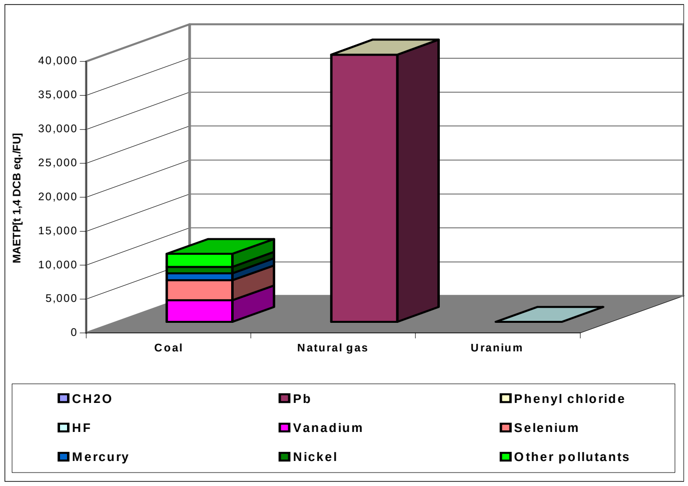
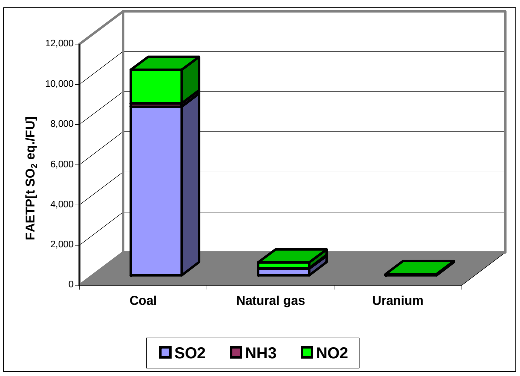


Fig.3.7 Assessment of the energy chains by MAETP indicator.



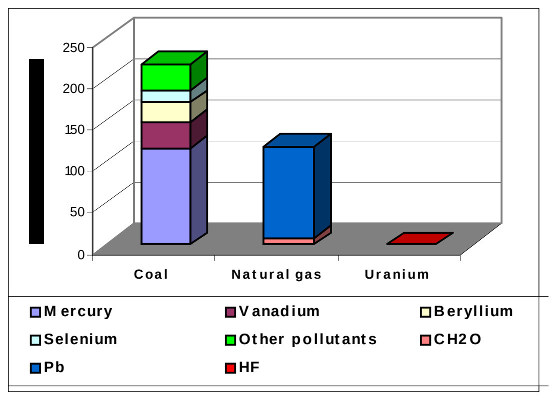


Fig. 3.8 Assessment of the energy chains by the AP indicator.

Fig. 3.9 Assessment of the energy chains by the TETP indicator.

- 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 uranium chain presents a value of 60 t 1,4 DCB eq. for the same indicator mainly due to the NO_2 emission (63%).
- 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 60 t SO_2 eq. for the uranium chain, the pollutants causing this impact category being SO_2 which contributes approximately 76% and NOx 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 uranium chain the registered value is 4 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 uranium chain it reaches approximately 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 only 3 t ethene equivalent for the uranium 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 uranium 0,4 t 1,4 DCB eq. covered 100% by HF.
- 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 uranium chain the value of this indicator is 5 t 1,4 DCB eq. of which HF 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 uranium chain the indicator value is insignificant as compared with the natural gas and coal chains (0.0003 t 1,4 DCB eq.).

5. Sensitivity analysis

Within this analysis the influence of the impact classes in establishing the environmental optimum energy chain has been determined. To this goal, the impact indicators have been divided into three classes as follows:

- ***Class 1*** is made up of the following impact indicators: GWP and ADP;
- ***Class 2*** is made up of the following impact indicators: AP, EP, FAETP, MAETP and TETP;
- ***Class 3*** is made up of the following impact indicators: POCP, HTP and IIR.

Considering that the assessment of the energy chains by the impact classes established within paragraph 4 do not have values reported at the same scale, a normalization of the assessments is necessary. Therefore, the normalization of the values within the [0,1] interval, developed by means of the relation given below has been considered:

$$N_i = \frac{E_i}{E_{\max}}, \text{ Where:} \qquad (2)$$

E_i represents the assessment of the energy chains by the i impact class;

E_{max} represents the maximum value between the assessments of the energy chains by the same i impact class.

The normalized matrix is given in table 11, and the graphical representation is developed in Fig. 4.

Table 11

Normalized matrix

Filiere	GWP	ADP	AP	EP	FAETP	MAETP	TETP	POCP	HTP	IIR
F_1	1	1	1	1	1	0.255	1	1	1	0
F_2	0.496	0.489	0.065	0.189	0.137	1	0.543	0.112	0.3770	0
F_3	0.018	0.00001	0.006	0.008	0.0007	0.0001	0.000001	0.007	0.0017	1

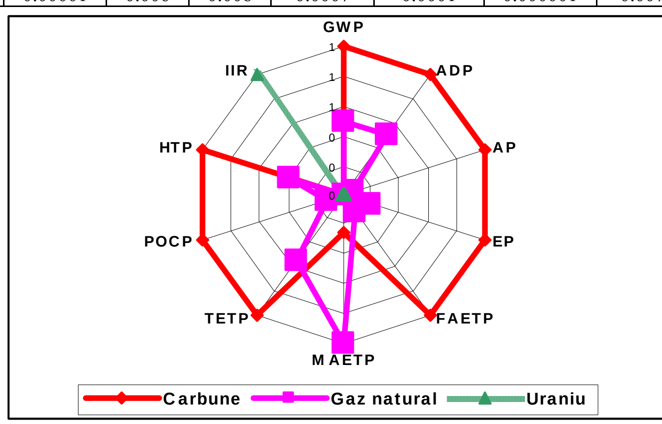


Fig.4 The global evaluation of the coal, natural gas and uranium life cycle

In the table 11, F_1 represents the coal chain, F_2 is the natural gas chain and F_3 the uranium chain.

Fig. 4 points out that the coal chain has the highest maximum value for the majority of impact indicators, the natural gas chain, in general, has average values for the same impact indicators, while, in the case of the uranium chain there is only one maximum value, that for the IIR impact indicator. Nevertheless, it is not certain whether the coal chain is the most polluting one. In order to determine this it is necessary to make the sensitivity analysis where the „classes of impact indicators”, defined above, have different shares.

When calculating the normalized matrix it was considered that all the impact classes have the same share. Further, the shares corresponding to the impact classes are presented. The meaning of the share values is the following: value „1” for the minor impact and the value „5” for major impact, respectively.

Three cases were analyzed:

Case 1: class I is given the value 5, while all the other classes the value 1;

Case 2: class II is given the value 5, while all the others, the value 1;

Case 3: class III is given the value 5, while all the others, the value 1.

Table 12 presents the results obtained in the three cases.

Based on the energy chain assessments and considering the three large classes, three triangles were formed whose area was calculated by means of Heron’s formula, considering that the area of a triangle, in general, with the a,b and c sides and the semiperimeter p=(a+b+c)/2 is:

$$S = \sqrt{p(p-a)(p-b)(p-c)}\ , \qquad (3)$$

Table 12

Assessment of the energy chains

Case 1	Class I-"5"	Class II-"1"	Class III-"1"
F1	10	4.26	2
F2	4.93	1.93	0.49
F3	0.09	0.01	1.01
Case 2	Class I -"1"	Class II-"5"	Class III-"1"
F1	2	21.28	2
F2	0.99	9.67	0.49
F3	0.02	0.07	1.01
Case 3	Class I -"1"	Class II-"1"	Class III-"5"
F1	2	4.26	10
F2	0.99	1.93	2.45
F3	0.02	0.01	5.04

The greater the area, the greater the global impact of the respective chain.

This enables us to obtain a single evaluation for each energy chain. Table 13 presents the single evaluations for each energy chain in all the three cases. It should be noticed that in all the three cases the most polluting chain is the coal one, followed by the natural gas and uranium.

Table 13

Single evaluation of the energy chains

	Case I	Case II	Case III
F1 – coal	23.89	30.15	23.89
F2 – natural gas	4.94	5.32	2.82
F3 – uranium	0.05	0.04	0.06

6. Conclusions

The paper carries put a global analysis of the coal, natural gas and uranium chains including: the inventory analysis (quantitative analysis), impact analysis (qualitative analysis) and sensitivity analysis (selection of the optimum ecological chain).

As a result of the inventory analysis the main pollutants generated along the life cycles have been identified. Thus, within the coal chain the main pollutants are carbon dioxide (CO_2=1,020,011 t/UF), dust particles (PM_{10}=9,205 t/UF), sulfur dioxide (SO_2=6,699 t/UF), nitrogen dioxide (NO_2=3,350 t/UF) and methane (CH_4=912 t/UF). The main pollutants generated during the life cycle of natural gas are: carbon dioxide (CO_2=437,909 t/UF), methane (CH_4=3,740 t/UF), nitrogen dioxide (NO_2=561 t/UF), carbon monoxide (CO=283 t/UF), sulfur dioxide (SO_2=275 t/UF). During the uranium life cycle, the radioactive emissions are much lower from the quantitative point of view than the non-radioactive ones. The main non-radioactive emissions generated are: CO_2=18,700 t/UF, SO_2=40 t/UF, NO_2=30 t/UF and CH_4=10 t/UF.

Within the impact analysis the impact classes based on the collected pollutants in the inventory analysis were established. The impact analysis made it possible to determine the contribution of each pollutant from the respective impact class. The main conclusions that have been drawn have been: from the point of view of the impact indicator the "natural resources depletion-abiotic depletion", the coal chain has the highest value (6,527 t Sb eq.) against the value registered for the natural gas (3,192 t Sb eq.). The value corresponding to the uranium chain is much lower, only 0.086 t Sb eq. From the point of view of the "global warming impact indicator, the coal chain registers a value of 1,040,558 t CO_2 eq., and the natural gas a value of 516,631 t CO_2 eq. The value for uranium is only 19,071 t CO_2 eq.. The main pollutant contributing to this impact class is CO_2, the latter participating 98% in the case of the coal and uranium chains and 85%, respectively, in the case of the natural gas chain. Moreover, within the last chain, methane emission has a 15% share mainly generated during the extraction and transport stages. By analyzing the „human toxicity" impact indicator, 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 is approximately 12,800 t 1,4 DCB eq., mainly due to the lead emissions in the soil, generated in the treatment stage (94%). For the same indicator, the uranium chain presents the value of 60 t 1,4 DCB eq., mainly due to the NO_2 (63%) emission.

The sensitivity analysis enabled the selection of the optimum chain from the environmental point of view (utilizing the impact indicators calculated during the de impact analysis as criteria). In conclusion, the uranium chain is the least polluting one. Even when considering the ionizing radiation impact indicator the hierarchy of the three energy chains analyzed in this study remains unchanged. On the other hand, the coal chain has a major environmental impact, but this is also due to the fact that the energy solution utilized has not envisaged flue gas treatment installations.

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