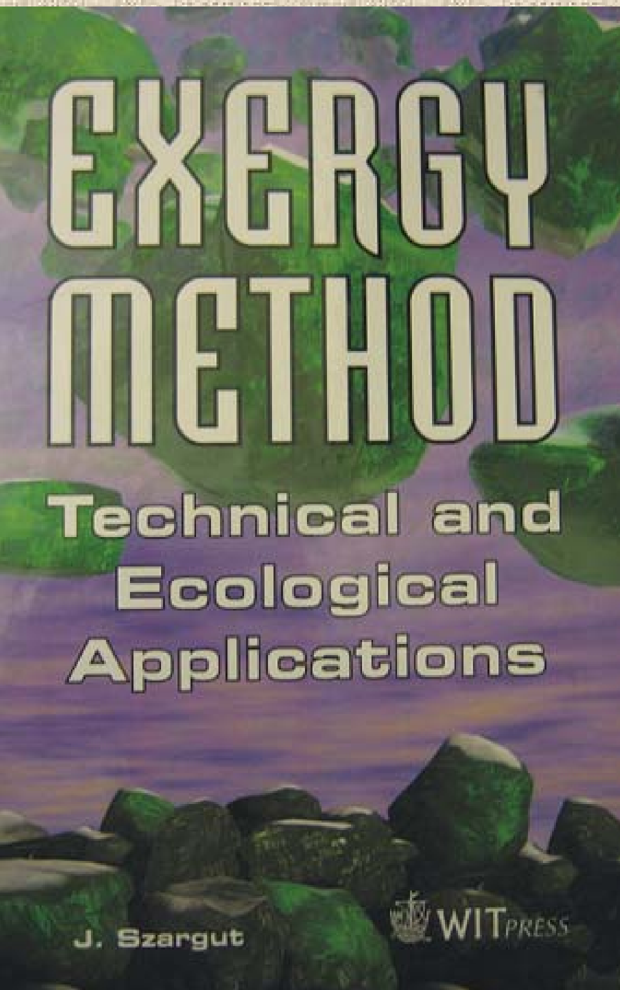
Thermo-Ecological Cost Analysis Theory and Applications

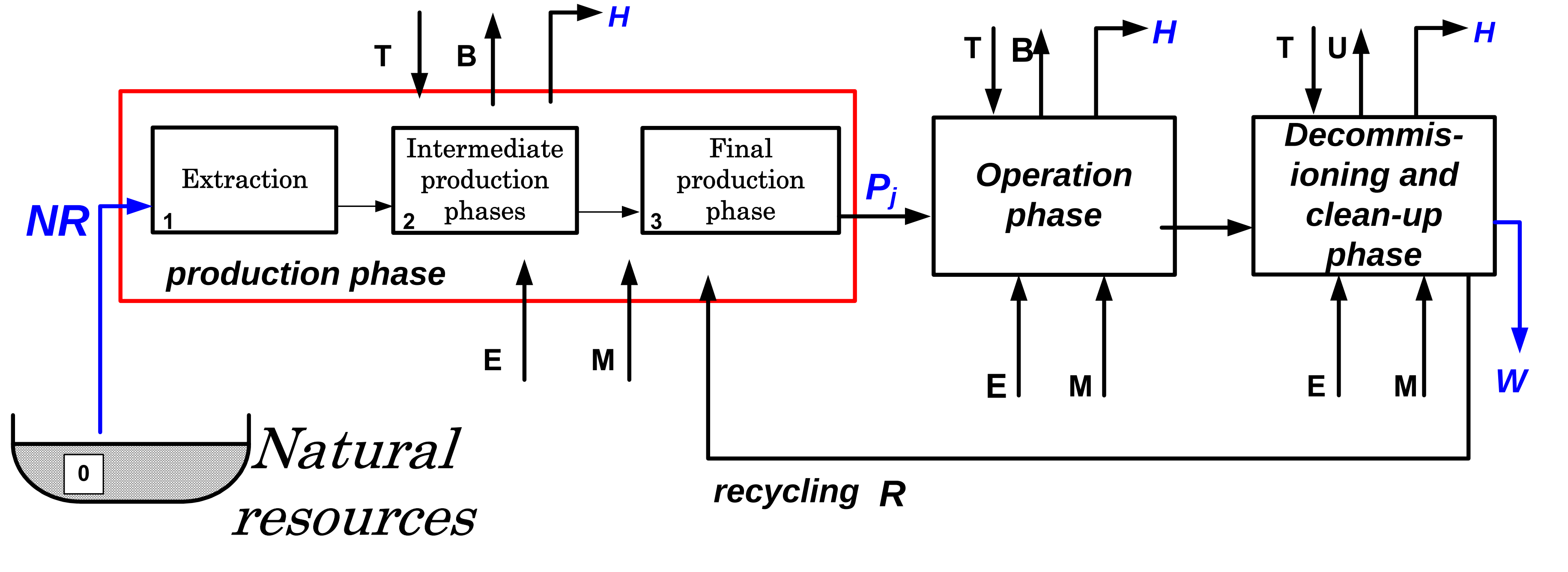
Wojciech STANEK
stanek@itc.polsl.pl

Silesian University of Technology
Institute of Thermal Technology
Gliwice, POLAND



ECOS'2005
Trondheim
NORWAY

1. General Concept of the Thermo-Ecological Cost

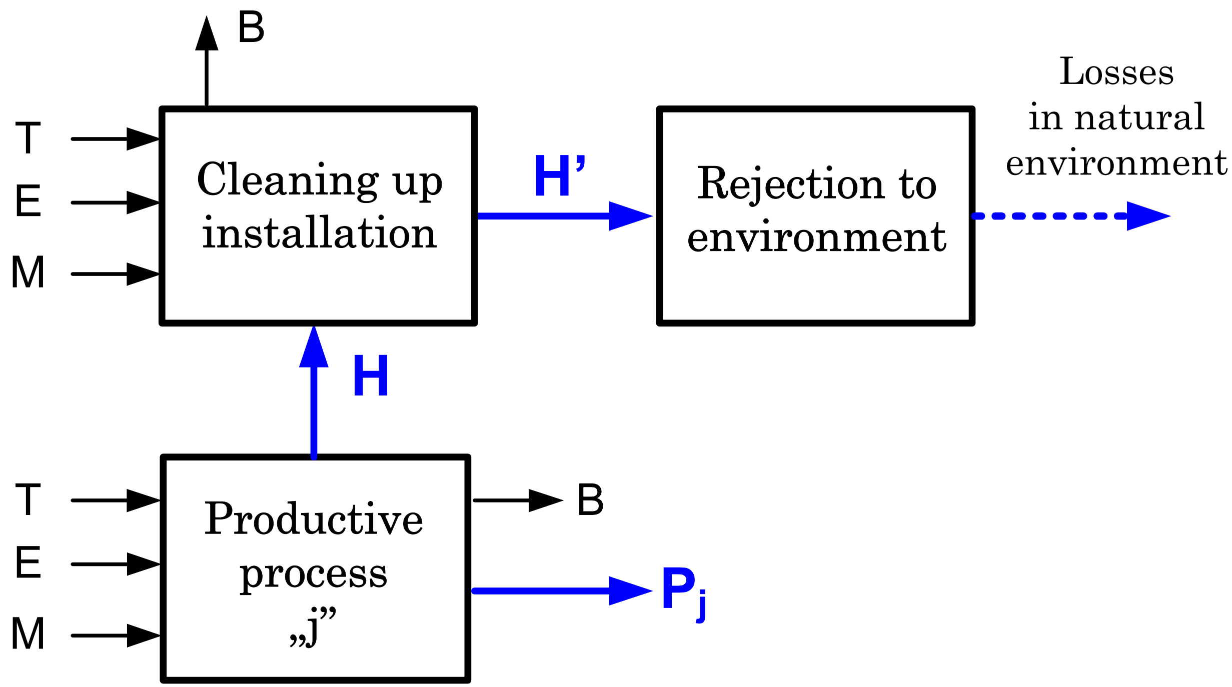


Characteristics phases within the life-time of product or system

Unfavourable influence of human activity upon environment

1) depletion of <u>limited</u> non-renewable natural resources
2) rejection of harmful substances to the natural environment

1. General Concept of the Thermo-Ecological Cost



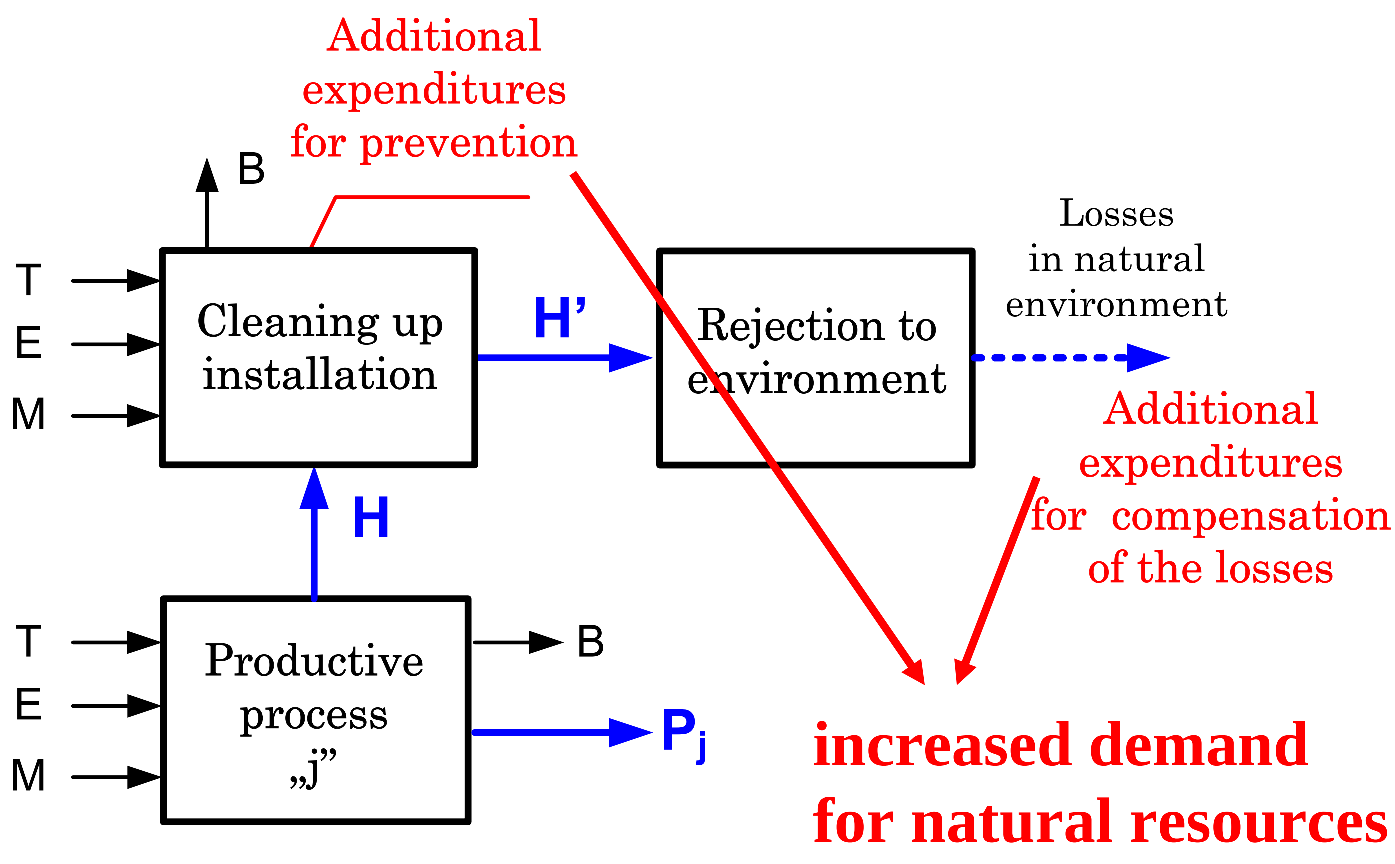
Rejection of the harmful substances to the natural environment

1. General Concept of the Thermo-Ecological Cost

Rejection of the harmful waste substances leads mainly to losses in the following fields:

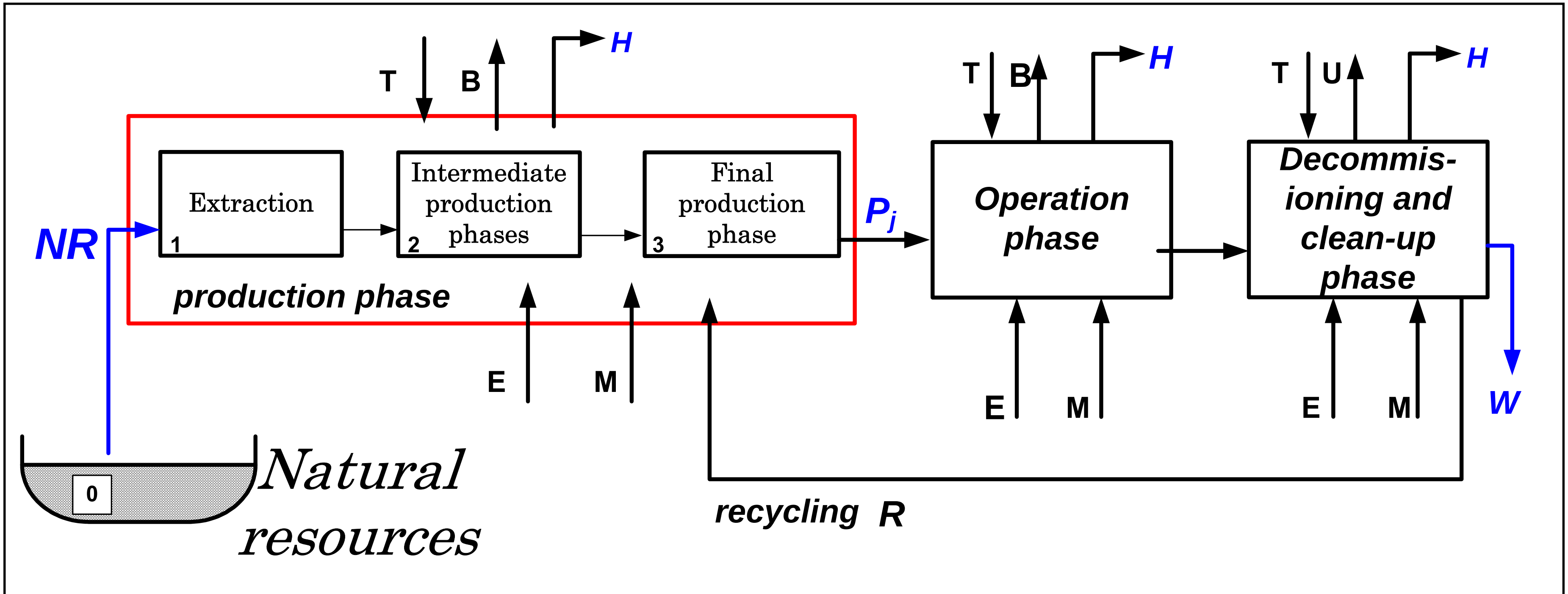
human health	→	**demand for additional health preventives and medicines**
useful industrial or other manufactured products corrosion of - machines - buildings - transportation equipment etc.	→	**demand for additional products replacing damaged ones or demand for additional expenses for corrosion prevention**
agricultural and foresttal production	→	**demand for additional expenses for compensation losses**

1. General Concept of the Thermo-Ecological Cost



Rejection of the harmful substances to the natural environment

1. General Concept of the Thermo-Ecological Cost



Characteristics phases within the life-time of product or system

Depletion of non-renewable natural resources results from:

1) demand for raw materials and semi-finished products

2) necessity of prevention or compensation the ecological losses

1. General Concept of the Thermo-Ecological Cost

Human activities is possible thanks to the use of natural resources

Part of them belongs to the group of non-renewable resources

Depletion of such resources presents crucial danger from the point of view of future existence of humankind

THE MAIN AIM OF ECOLOGICAL ECONOMY

Minimisation of consumption non renewable natural resources during designing and operation of productive processes

1. General Concept of the Thermo-Ecological Cost

Different energy carriers as well as different natural resources are characterized by different quality

It is necessary to determine the common measure of the quality of natural resources

1. General Concept of the Thermo-Ecological Cost

Evaluation of Natural Capital – Standard Economy

Only concerns with what being:
i. directly useful to man,
ii. is also acquirable, valuable and produce-able.

The price-fixing mechanisms, rarely take into account the concrete physical characteristics which make them valuable.

For this reason, most of the natural resources, remain outside the object of analysis of the economic system.

1. General Concept of the Thermo-Ecological Cost

Evaluation of Natural Capital – Exergy

Physical features which make natural resources unusual:

a particular composition which differentiates them from the surrounding environment

distribution which places them in a specific concentration

This intrinsic properties, can be in fact evaluated from a thermodynamic point of view in terms of **exergy**

1. General Concept of the Thermo-Ecological Cost

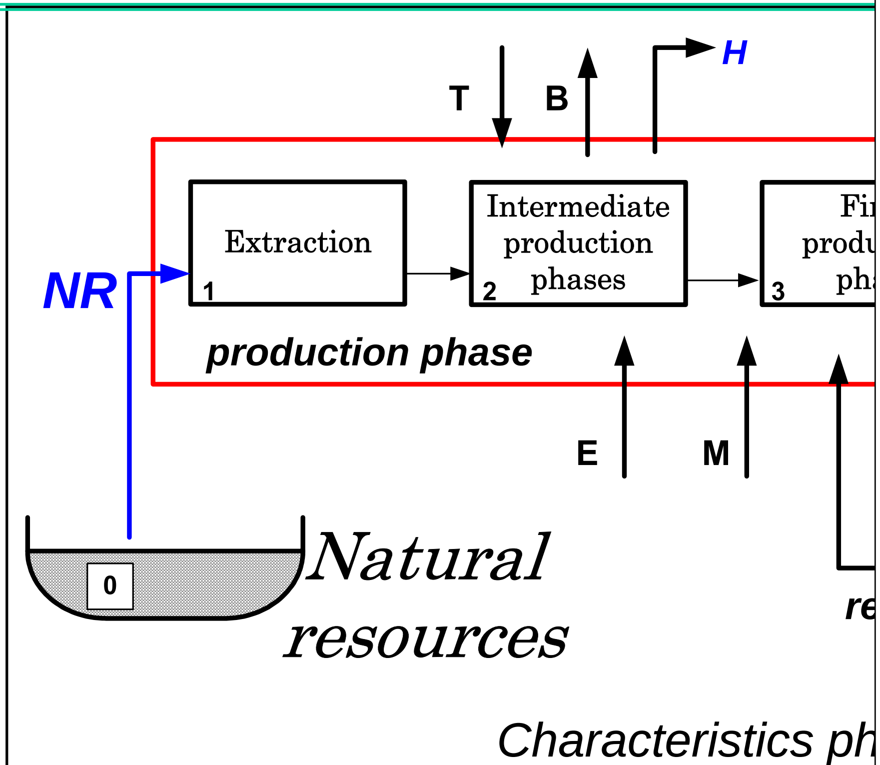
Evaluation of Natural Capital – Exergy

The thermodynamic value of a natural resource could be defined as the minimum work necessary to produce it with a specific structure and concentration from common materials in the environment.

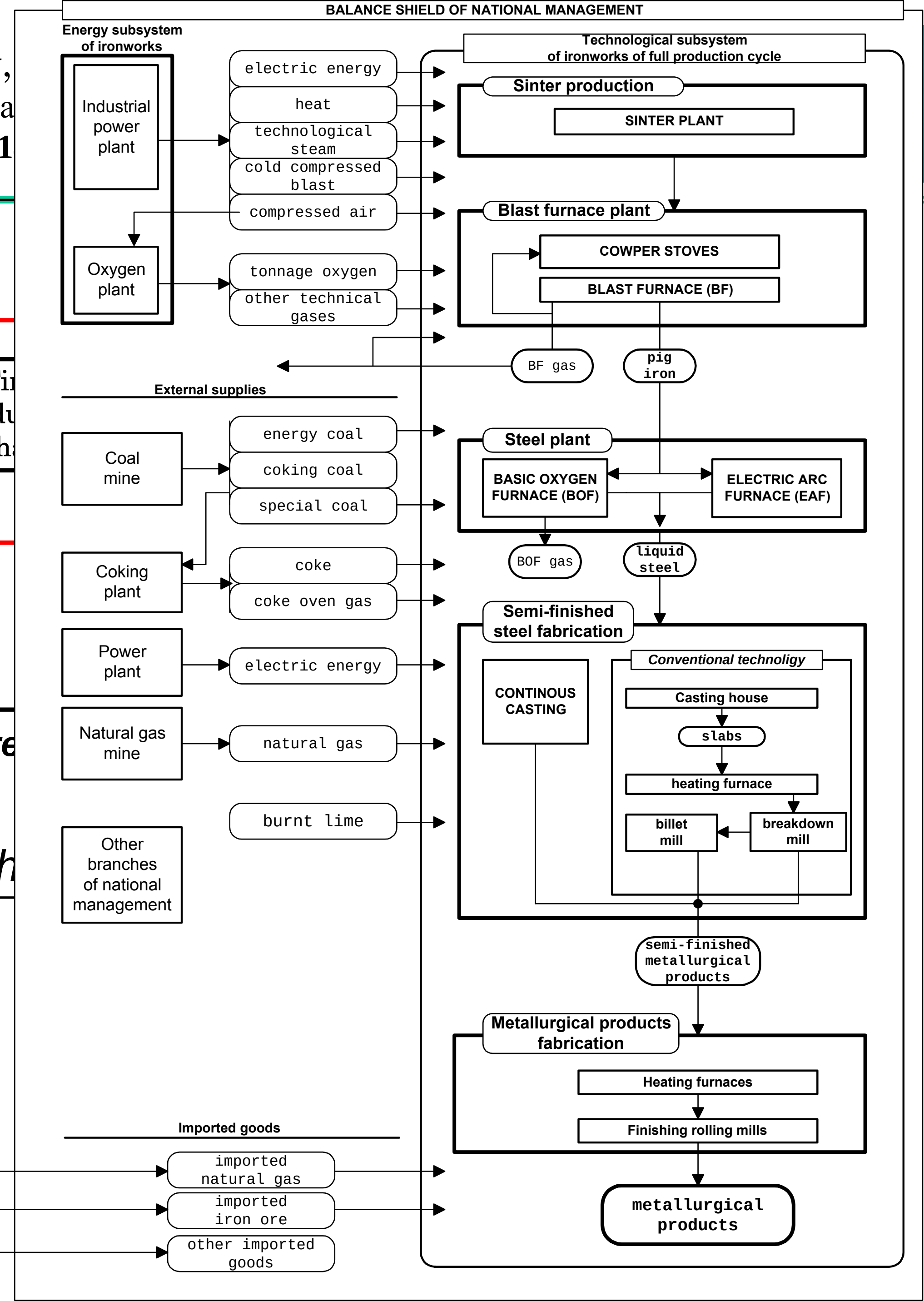
This minimum amount of work is theoretical by definition and is equal to the material's exergy

THERMO-ECOLOGICAL ANALYSIS

EXERGY – measure of natural resource quality



COMPLETE EXPENDITURES:
cumulative consumption of
- **energy**
- **exergy**
- **emission**



1. General Concept of the Thermo-Ecological Cost

EXERGY

common measure of the quality of natural resources

COMPLETE EXPENDITURES

calculus of cumulative consumption

THERMO-ECOLOGICAL COST (J. Szargut)

cumulative consumption of non-renewable exergy connected with the fabrication of a particular product, with the additional inclusion of the consumption resulting from the necessity of compensation the environmental losses caused by release of harmful substances.

2. Methodology of calculation of the thermo-ecological cost

Evaluation of deleterious impact of waste products by means of their monetary index of harmfulness (J. Szargut)

$$\zeta_k = \frac{B w_k}{DCP + \sum_k P_k w_k}$$

B - annual exergy consumption of non-renewable natural resources

DCP -

P_k -

DCP = monetary value of all useful products used in the consumption sector, expect those used in production processes

on

w_k - monetary coefficient of ecological damages per unit of the *k*-th aggressive waste product

ζ_k - cumulative exergy consumption of non-renewable resources due to the emission of unit of the *k*-th waste product

$$\sum_i a_{ij}\rho_i$$

ecological cost of domestic energy carriers and semi-finished products

$$\sum_r a_{rj}\rho_r$$

ecological cost of imported goods

$$\sum_s b_{sj}$$

direct non-renewables exergy consumption

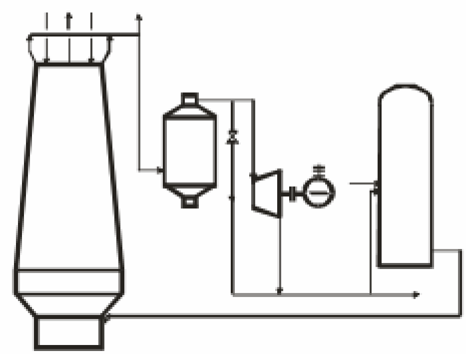
$$\sum_k p_{kj}\zeta_k$$

ecological cost of emissions

$$\sum_u i_{uj}\rho_u$$

ecological cost of specific investment expenditure

THERMO- -ECOLOGICAL COST OF PRODUCT "j"



$$\sum_i f_{ij}\rho_i$$

ecological cost of by-product(s)

$$\rho_j$$

thermo - ecological cost of j-th main product

Balance Equation of the Thermo – Ecological Cost

$$\rho_j + \sum_i (f_{ij} - a_{ij})\rho_i - \sum_r a_{rj}\rho_r = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k$$

a_{ij}, f_{ij} - coefficient of the consumption and by-production of the i-th product per unit of the j-th major product

a_{rj} - coefficient of the consumption of r-th imported product per unit of the j-th major product

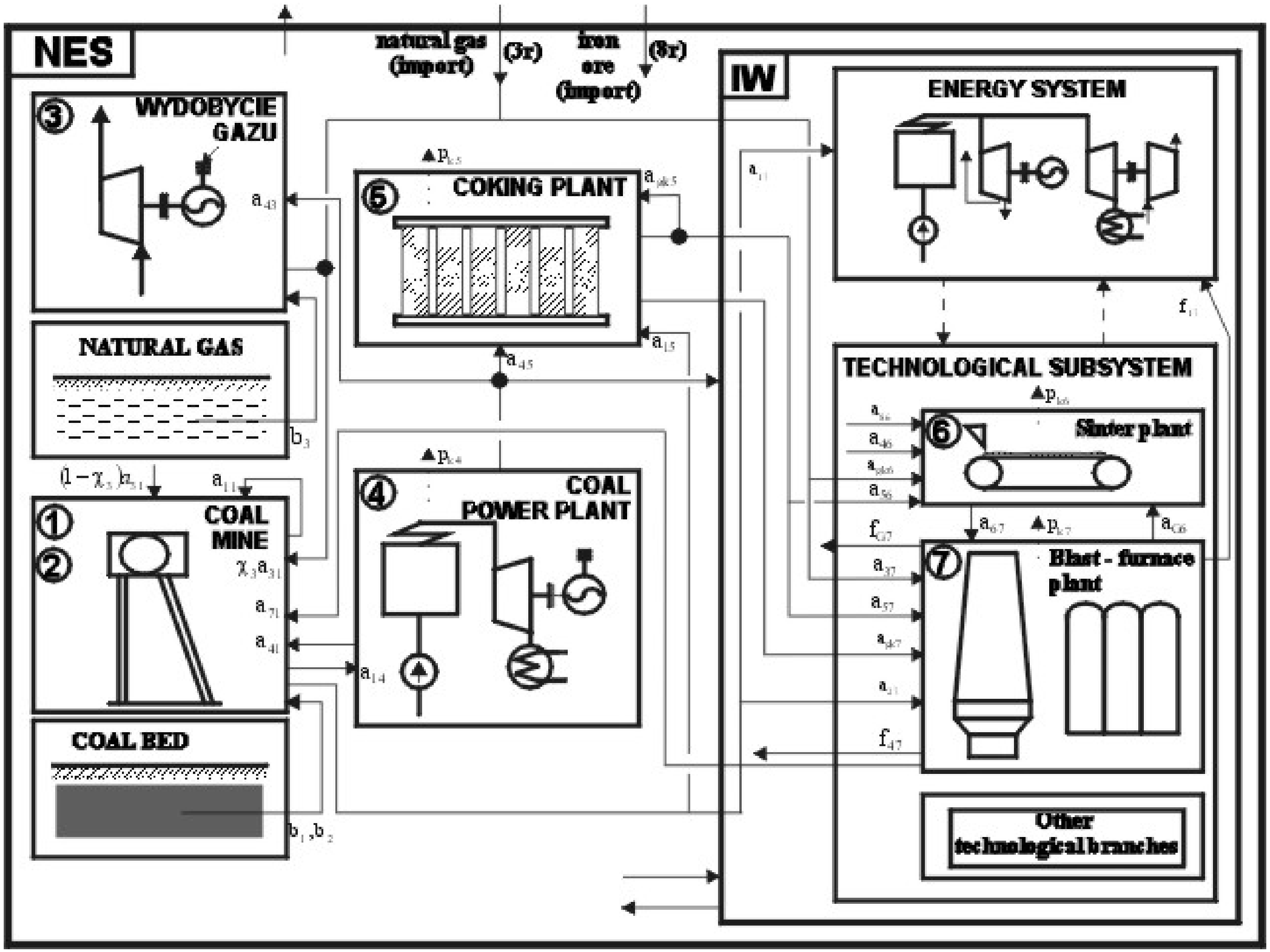
b_{sj} - exergy of the *s*-th non-renewable natural resource immediately consumed in the process under consideration per unit of the *j*-th product

ρ_j, ρ_i, ρ_r - indices of the thermo-ecological cost of the j-th, i-th, and r-th product

p_{kj} - amount of the *k*-th aggressive component of waste products rejected to the environment per unit of the *j*-th product

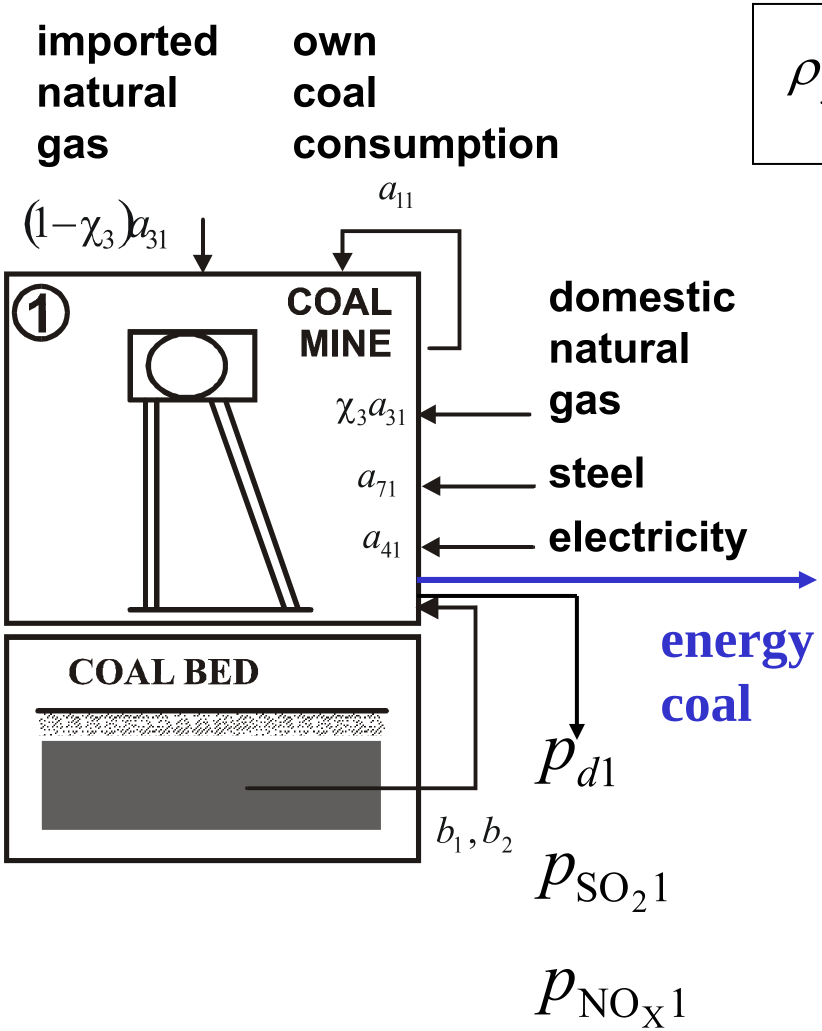
ζ_k - cumulative exergy consumption of non-renewable resources due to the emission of unit of the *k*-th waste product

All processes are interconnected cumulative analysis



Example equation - coal mine j=1

$$\rho_j + \sum_i f_{ij}\,\rho_i - \sum_i a_{ij}\,\rho_i - \sum_r a_{rj}\rho_r = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k$$



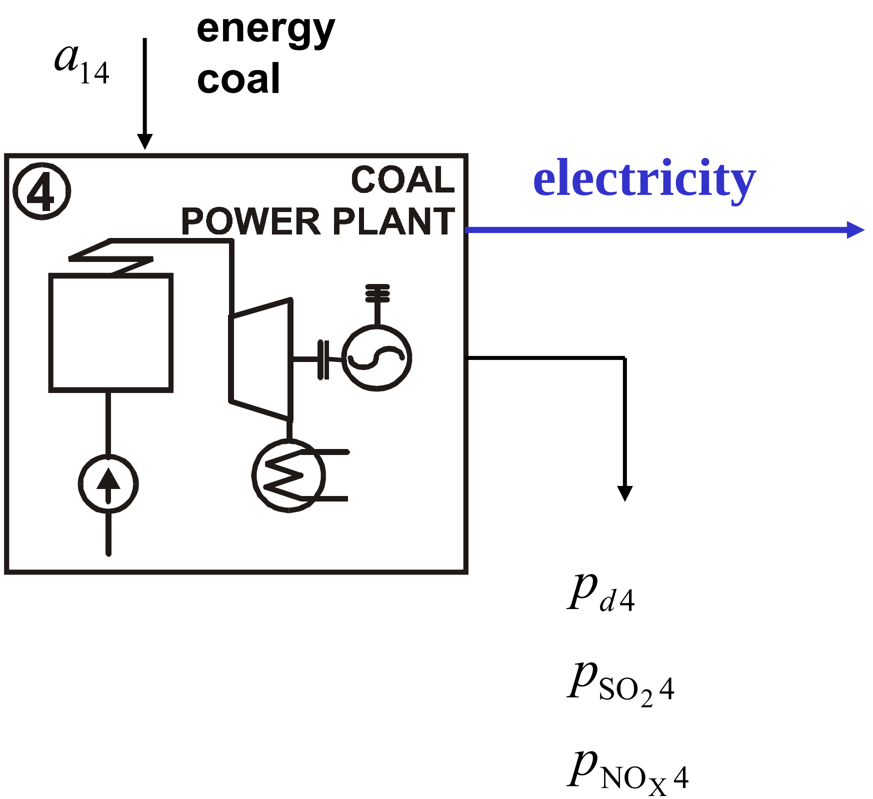
$$(1-a_{11})\rho_1 - \chi_3 a_{31}\rho_3 - a_{41}\rho_4 - a_{71}\rho_7 =$$
$$= b_1 + (1-\chi_3)a_{31}\rho_{3r} + \sum_k p_{1k}\zeta_k$$

a_{11}=0.0058 kg/kg, a_{31}=0.000041 kmol/kg,
a_{41}=0.175 MJ/kg, a_{71}=0.004 kg/kg,
a_{22}=0.0058 kg/kg, a_{32}=0.000041 kmol/kg,
a_{42}=0.175 MJ/kg, a_{72}=0.004 kg/kg
b_1 = 21.80 MJ/kg

$p_{SO2\ 1} = p_{NOx\ 1} = p_{d\ 1}$ = 0.0001 kg/kg

Example equation - coal power plant j=4

$$\rho_j + \sum_i f_{ij}\,\rho_i - \sum_i a_{ij}\,\rho_i - \sum_r a_{rj}\rho_r = \sum_s b_{sj} + \sum_k p_{kj}\zeta_k$$



$$\rho_4 - a_{14}\rho_1 = \sum_k p_{4k}\zeta_k$$

a_{14}=0.124 kg/MJ ($\eta_{el} = 0.35$)

$p_{SO2\,4} = 0.00218$ kg / MJ
$p_{NOx\,4} = 0.00101$ kg / MJ
$p_{d\,4} = 0.00347$ kg / MJ

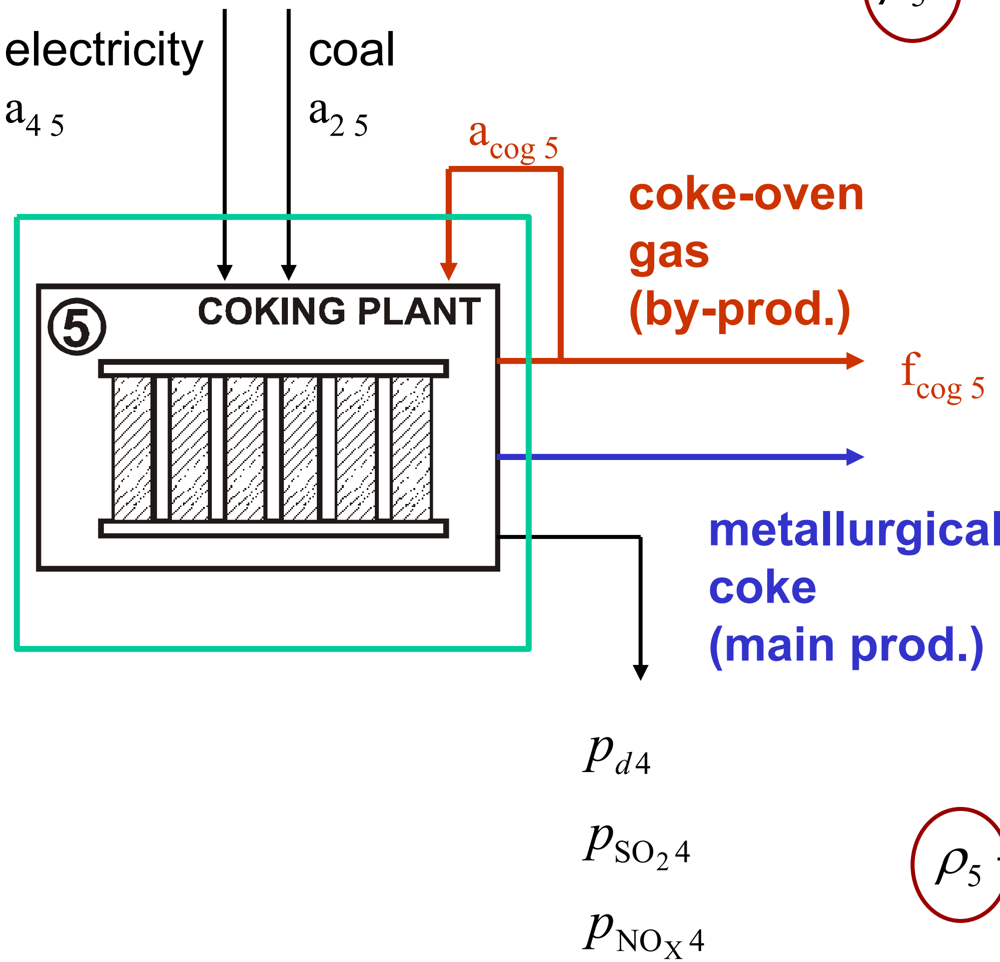
2. Methodology of calculation of the thermo-ecological cost

A. THERMO-ECOLOGICAL COST OF BY-PRODUCTS

Division of the energy consumption or costs between main product and by-products – method of avoided costs (method of replaced process):

the by-product should be burdened by equivalent costs or energy consumption resulting from the effects of the replacement by other products

method of avoided costs



$$\rho_5 + a_{25}\rho_2 - a_{45}\rho_4 - \left(a_{cog\,5} - f_{cog\,5}\right)\rho_{cog} = \sum_k p_{5k}\zeta_k$$

effects of substituting the natural gas by coke oven gas

$$a_{cog\,5}\rho_{cog} = a_{35}\rho_{3r\,5}, \quad f_{cog\,5}\rho_{cog} = f_{35}\rho_{3r5}$$

$$a_{35} = \nu_{ng-cog}\, a_{cog\,5}$$

$$f_{35} = \nu_{ng-cog}\, f_{cog\,5}$$

$$\nu_{ng-cg} \approx 1\frac{\text{MJ n. g.}}{\text{MJ c.o.g.}} = 0.5\frac{\text{kmol n. g.}}{\text{kmol c.o.g.}}$$

$$\rho_5 + a_{25}\rho_2 - a_{45}\rho_4 = \sum_k p_{5k}\zeta_k + (a_{35} - f_{35})\rho_{3r}$$

2. Methodology of calculation of the thermo-ecological cost

B. THERMO-ECOLOGICAL COST IMPORTED GOODS

Iterative method of calculation the thermo-ecological cost of imported goods

$$\rho_j + \sum_i f_{ij}\,\rho_i - \sum_i a_{ij}\,\rho_i - \sum_r \mathrm{a}_{rj}\,\rho_r = \sum_s \mathrm{b}_{sj} + \sum_k \mathrm{p}_{kj}\zeta_k$$

$$?\ \rho_r$$

STANEK W. *Iterative Method of Evaluating the Ecological Cost of Imported Goods*. ECOS'2001, Istanbul, Turcja 2001.

STANEK W. *Iterative Method to Evaluate the Ecological Cost of Imported Goods*. International Journal Applied Thermodynamics, Vol. 4 (No.4), 2001

STANEK W. *Wskaźniki kosztu ekologicznego krajowego eksportu*, Gospodarka Paliwami i Energią, No 10 2001

2. Methodology of calculation of the thermo-ecological cost

B. THERMO-ECOLOGICAL COST IMPORTED GOODS

Thermo-ecological cost analysis

global scale	regional scale (eg. domestic economy)
whole „interregional" exchange appears within the balance boundary	the ecological cost indices of imported goods represent the additional unknows
there are not necessity to introducting the ecological cost of imported goods into the balance equation set	to solve the set of equations some knowledge of the ecological cost indices of imported goods is necessary

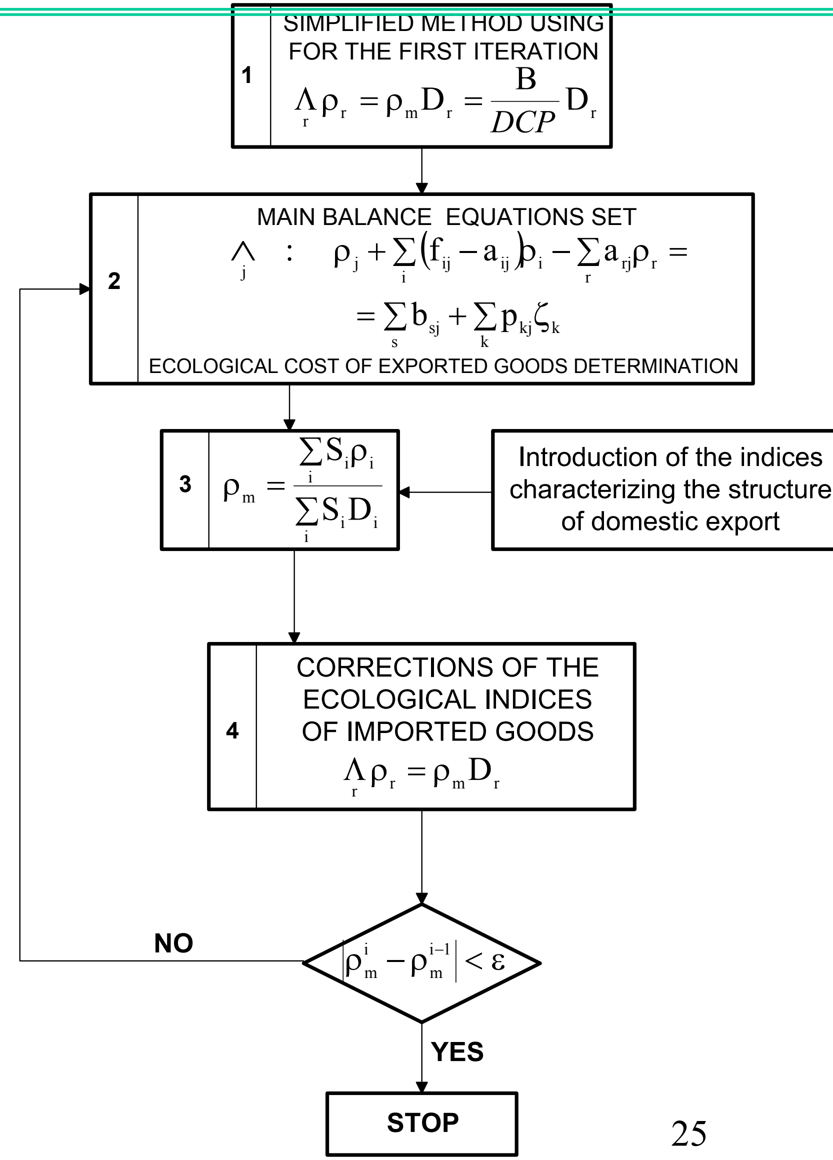
2. Methodology of calculation of the thermo-ecological cost

B. THERMO-ECOLOGICAL COST IMPORTED GOODS iterative algorithm

ρ_m - **ecological cost of the exported products, per monetary unit, MJ/€**

D_i, D_r - **monetary value of the *i*-th domestic and *r*-th imported product, €/kg, €/kmol**

S_i - **annual amount of *i*-th exported good, kg/a, €/a**



3. Minimization of the Thermo-Ecological Cost

What should be the aim of thermodynamic optimisation ?

Bejan A.: *A thermodynamic optimization aims at minimizing the thermodynamic inefficiencies: exergy destructions and exergy loss*

1. Maximization of exergy efficiency

   thermal power plant fed by chemical fuel $$\eta_B = \frac{N}{\dot{B}_{\mathrm{ch}F}} = \frac{N}{\dot{F} b_{\mathrm{ch}F}}$$

2. Minimization of consumption of fuel F

3. **In general: minimization of consumption of non-renewable resources**

3. Minimization of the Thermo-Ecological Cost

Method of thermodynamic optimisation

Use the value of entropy generation in considered process as the objective function which should be minimised for its thermodynamic optimisation (**internal exergy losses minimisation in considered process*****)***

1. That method is not consequent, because it does not take into account the entropy generation in the preceding processes delivering energy carriers and semi-finished products to the considered process.

3. Minimization of the Thermo-Ecological Cost

Method of thermodynamic optimisation

Use the value of entropy generation in considered process as the objective function which should be minimised for its thermodynamic optimisation (*internal exergy losses minimisation In considered process*)

2. The method cannot be consequently respected when analysing the utilization of renewable exergy taken from natural resources.

For example,
when optimizing the solar collector the entropy generation appearing in the considered system is proportional to the consumption of exergy of solar radiation. This consumption does not denote any economical or ecological loss, and therefore <u>should not be</u> accepted as the objective function for the optimisation.

3. Minimization of the Thermo-Ecological Cost

Thermo-ecological life cycle analysis - objective function

$$P_A = \tau_n \sum_j \dot{G}_j \rho_j + \frac{1}{\tau}\left[\sum_m G_m \rho_m (1-u_m) + \sum_r G_r \rho_r\right] \to \min$$

$\dot{G}_j, \rho_j$ - nominal flow rate and specific ecological cost of *j*-th Raw material, semi-finished product or energy carrier supplied to the production process

τ_n - annual operation time with nominal capacity

τ - nominal life time of the instalation (in years)

u_m - expected recovery factor of the *m*-th material after wearing the considered device

G_m, ρ_m - consumption and specific thermo-ecological cost *m*-th material or energy carrier used for the construction of the instalation

G_r, ρ_r - expected consumption and specific thermo-ecological cost of the *r*-th material or energy carrier used in repairs

4. Applications of the Thermo-Ecological Cost

1) influence of the operational parameters of energy and technological systems upon the depletion of non-renewable natural resources
2) selection of the kind of technology that ensures minimal consumption of non-renewable natural resources
3) optimisation of design and operational parameters to ensure minimum depletion of natural resources
4) evaluation of harmful impacts of waste products
5) investigation of the influence of interregional exchange upon the depletion of domestic natural resources
6) evaluation of the ecological harmfulness of particular useful goods in their whole life time (thermo-ecological life cycle analysis)
7) comparison of sustainability of different useful products
8) determination of pro-ecological tax replacing existing PIT and VAT

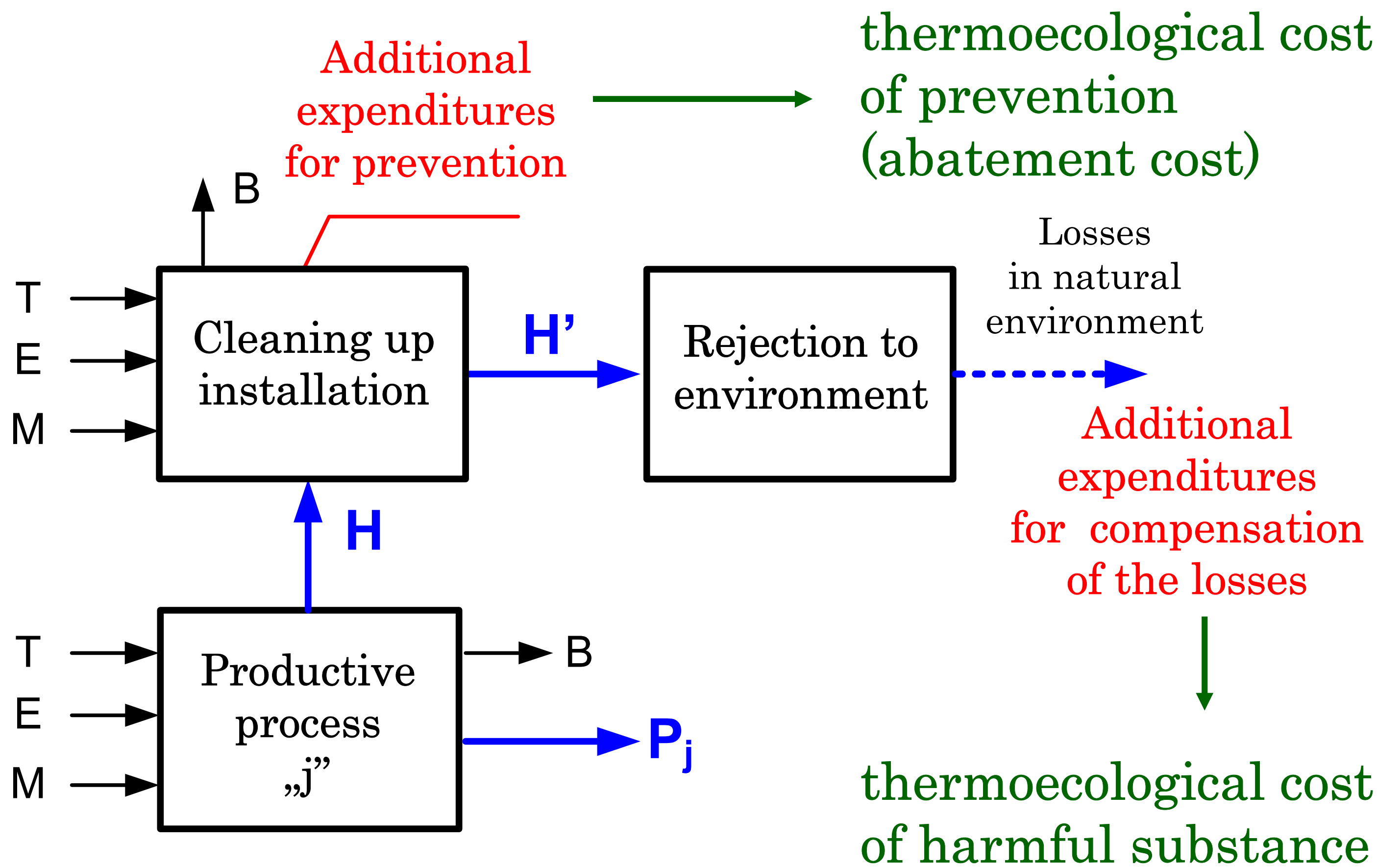
Thermo-Ecological Cost as a Measure of Sustaiability

$$r_i = \frac{\rho_i}{b_i} = \frac{\text{thermo - ecological cost}}{\text{specific exergy}}$$

Thermoecological cost of fuels

Energy carrier	b_{ch}	ρ	r
	MJ/um	MJ/MJ_E	MJ/MJ
Hard coal [1]	26.2	1.12	1.04
Coke[1]	31.8	1.58	1.45
Natural gas[2]	821.6	0.90	0.87
Natural gas[2] (domestic)	821.6	1.06	1.02
Natural gas[2] (import)	821.6	0.79	0.76
Coke-oven gas[2]	380.0	0.94	0.94

Evaluation of Harmful Impacts of Waste Products



Rejection of the harmful substances to the natural environment

Evaluation of Harmful Impacts of Waste Products

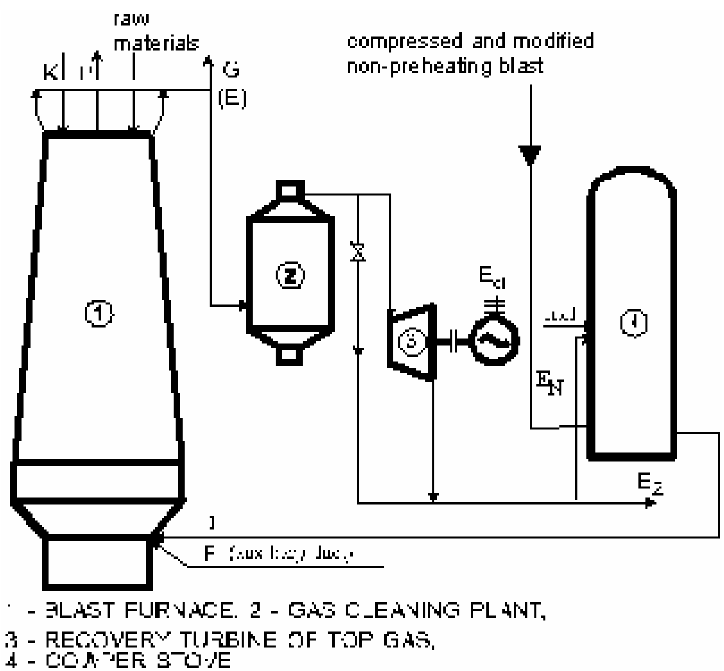
Comparison of thermoecological cost of prevention and rejection

Harmful substance	Thermoecological cost of prevention σ_k	Thermoecological cost of rejection ξ_k	Sustainability Index r_k
	MJ/kg	MJ/kg	MJ/kg
CO2	4.4	=	=
SOx	17.5	45.0	0.38
NOx	26	45.0	0.58
Pył	0.5	9.5	0.05

Share of thermoecological cost of prevention in the total amount of exergy of domestic coal
B – exergy of reserves, A – total prevention TH cost

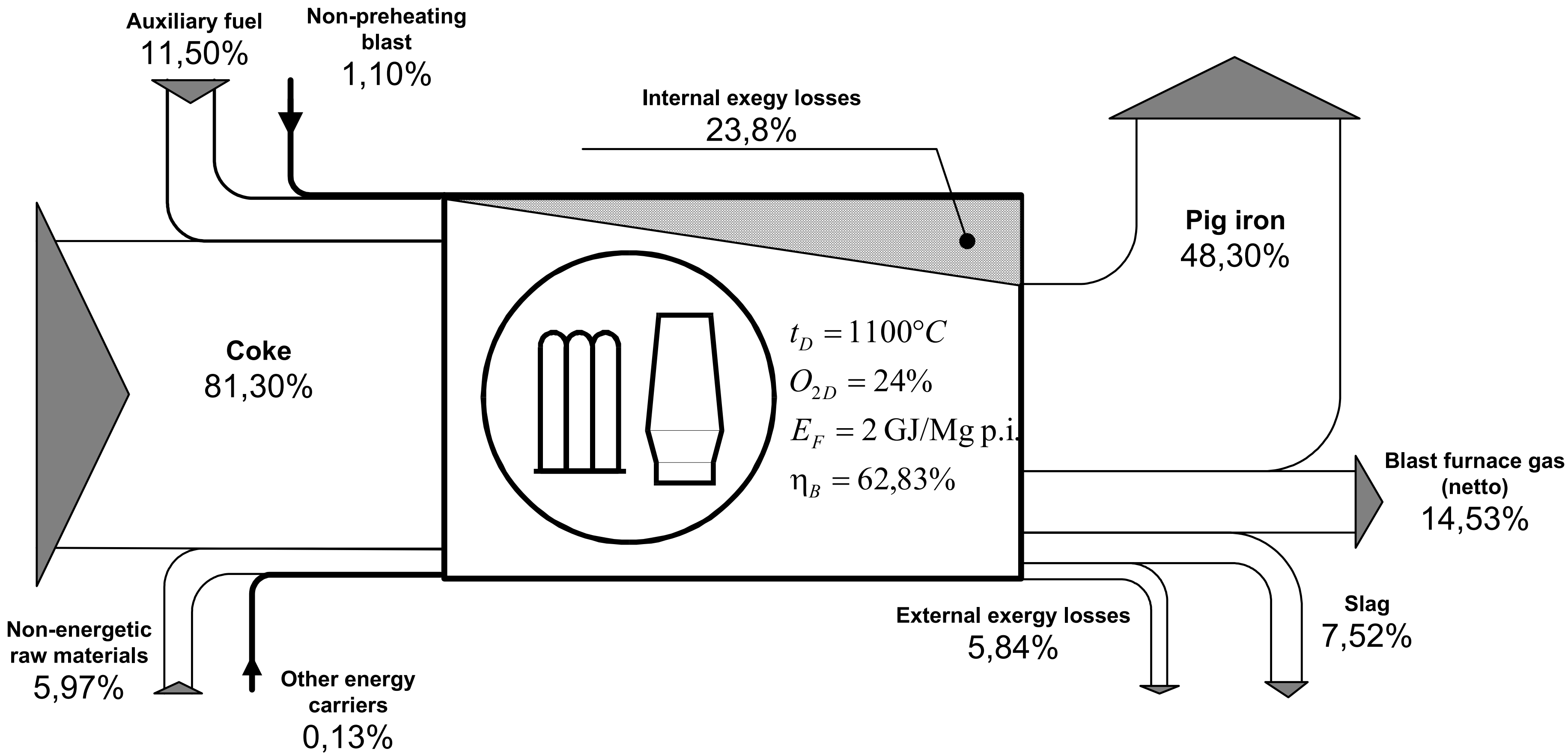
Resource	**B**	**A**	**A/B**
	PJ	PJ	%
Hard coal	1179412	21999.45	1.86
Lignite	125856	12265.08	9.74

Influence of the Operational Parameters of Energy and Technological Systems upon the Depletion of Non-renewable Natural Resources



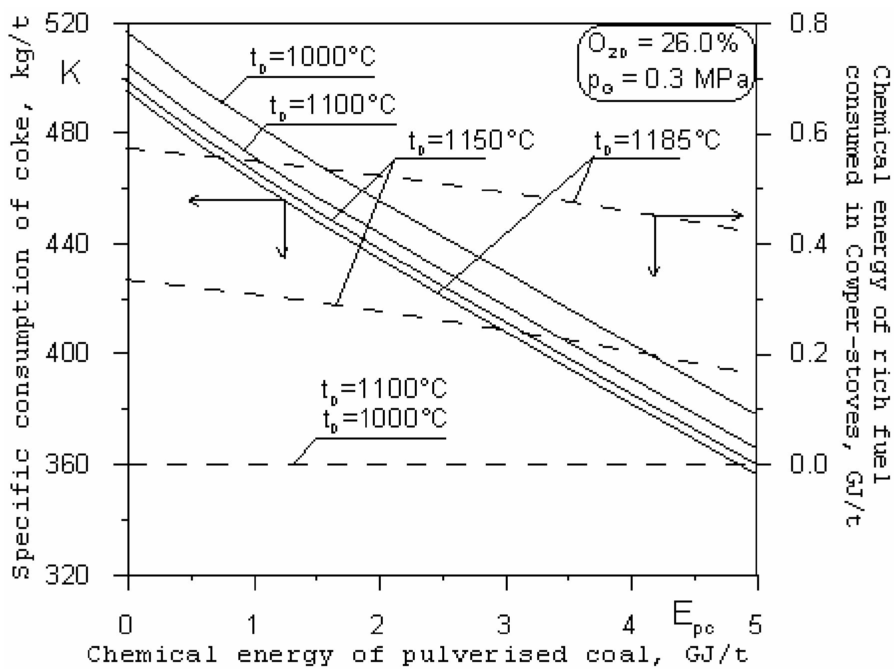
Input part of cumulative energy consumption of selected blast-furnace plant (without raw material)

Carrier	Cumulative energy consumption	
	TJ / year	%
Coke	**74706**	**81,94**
Blast	9148	10,03
Coke-oven gas	3083	3,38
Natural gas	1261	1,38
Electric energy	1316	1,44
Compressed nitrogen	1036	1,14
Compressed oxygen	54	0,06
Technological stem	326	0,36
Compressed air	193	0,21
Soft water	15	0,02
Industrial water	41	0,04
Σ	91179	100,00

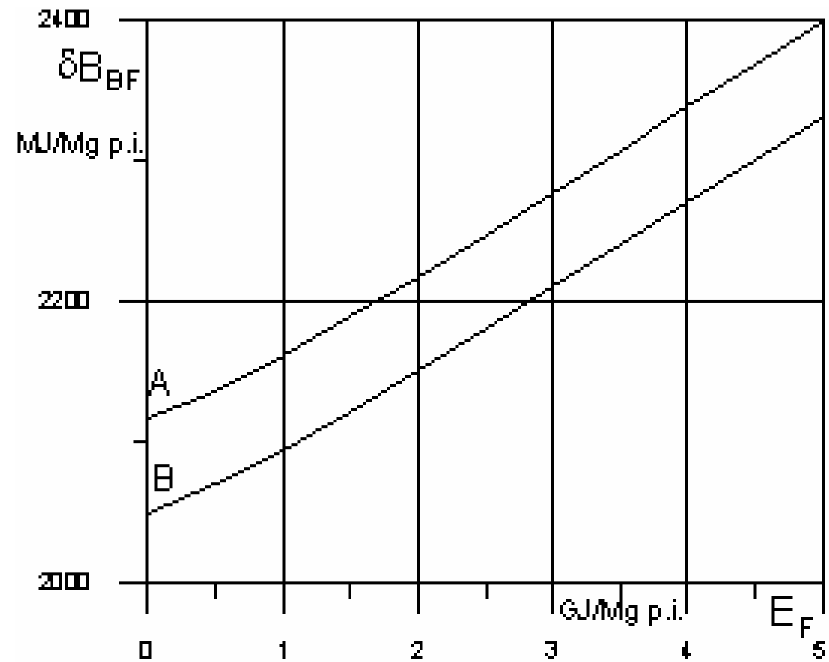


Flow diagram of the exergy balance
Blast-furnace process

Results of injection of pulverised coal into Blast-furnace



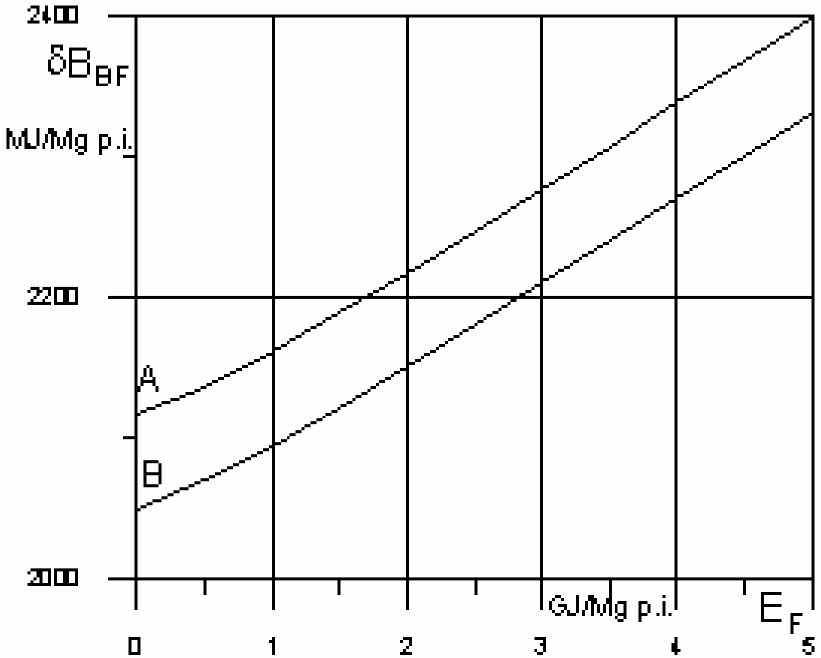
Specific consumption of coke

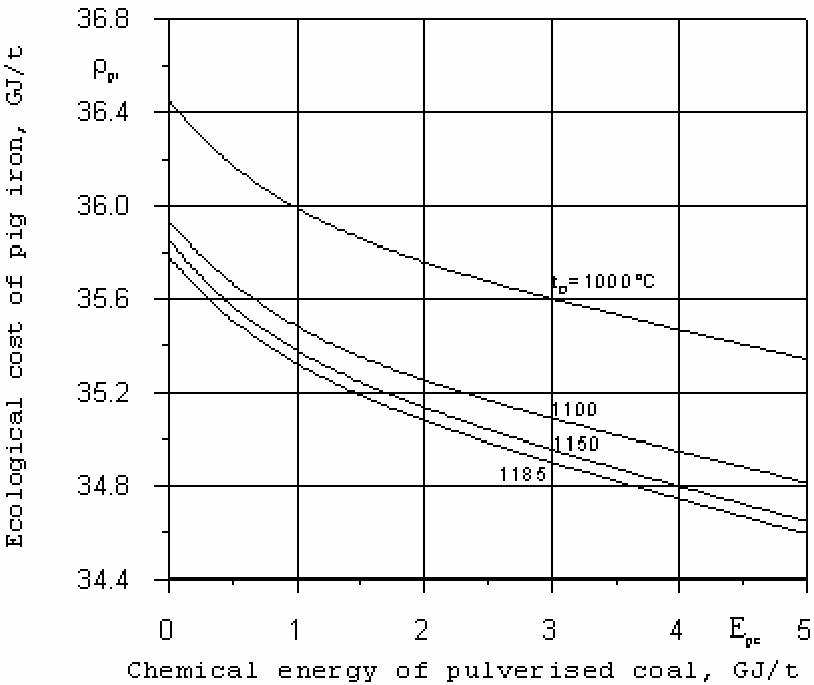


Internal exergy losses

From the point of view of minimisation of entropy generation in considered process the injection of pulverized coal into Blast furnace is not profitable

Comparison of inetrnal exergy losses and Thermo-Ecological Cost



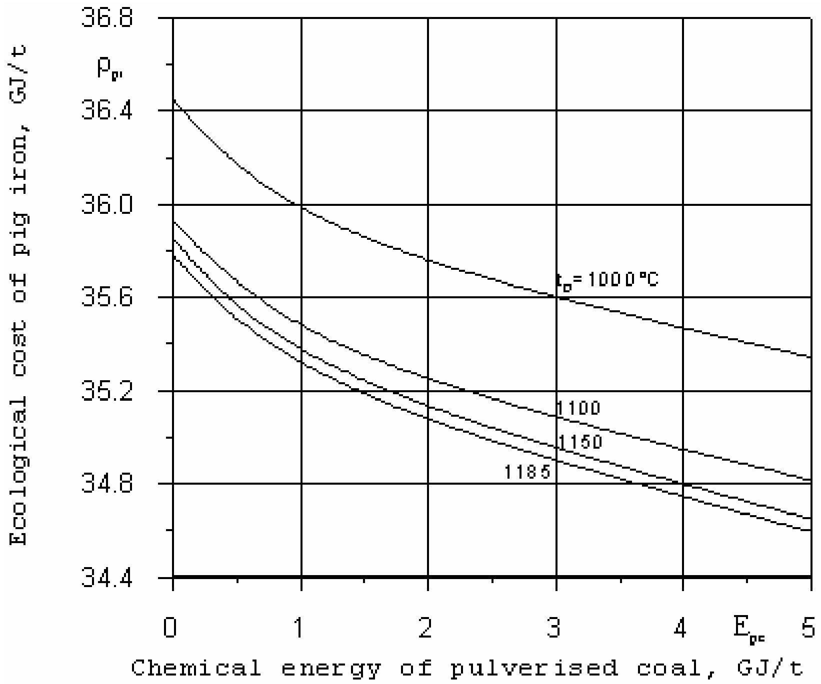


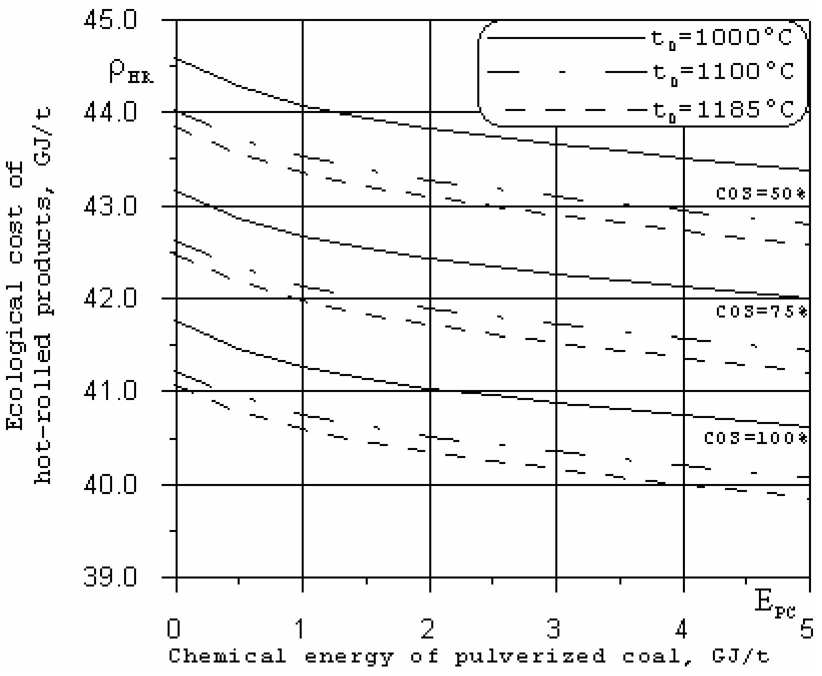
$r_{pc} = 1.07$, $r_c = 1.40$

PCI is most effective (from the economic point of view) way to replacement of the metellurgical coke in blast furnace

Also from the point of view of ecological economy PCI is profitable

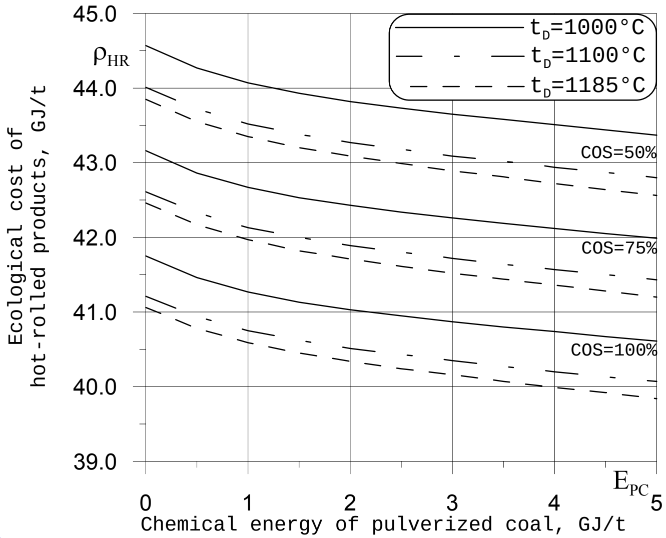
Influence of the Operational Parameters of Energy and Technological Systems upon the Depletion of Non-renewable Natural Resources

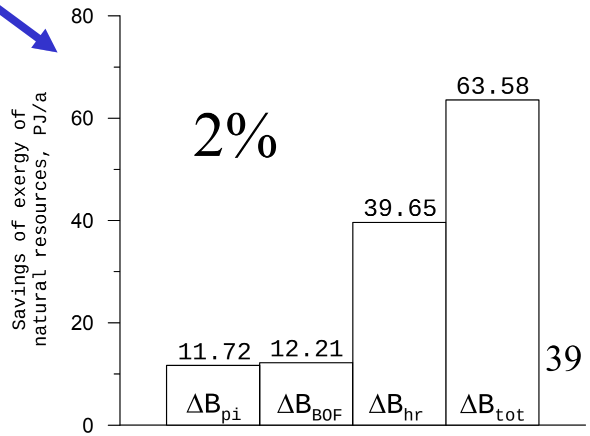




Optimization of operational parameters to ensure minimum depletion of natural resources - Blast-furnace process

A. Natural gas – practical parameters			
F, kmol/t	t_D, °C	O_{2D}, %	ρ_{sur} MJ/kg
1,978	1102	26,4	34,92
B. "Low parameters"			
0	1100	22	36,02
C. Coke-oven gas minimum			
6,047	1180,4	27	34,79
D. Natural gas minimum			
3,193	1183	27	34,68
E. Pulverised coal minimum			
179,5	**1185**	**27**	**34,50**





Optimization of design parameters to ensure minimum depletion of natural resources - Solar colector

$$A_{opt} = 7.5\ m^2,\quad d_{opt} = 10\ mm,\quad b_{opt} = 0.13\ m.$$

MODUŁ B

Założenie wstępnych wartości zmiennych decyzyjnych

$$d_0, b_0, A_0$$

Jednostkowa ilość ciepła produkowanego w kolektorze

$$q_c = \int_0^{\tau_{gr}} \dot{q}(\tau)\,d\tau$$

Roczna produkcja ciepła w kolektorze

$$Q_k = A\zeta\chi - Q_n$$

Roczny koszt termoekologiczny (funkcja celu)

$$K_{TE1} = \frac{1}{\tau}\left[G_c\rho_c(1-u_c) + G_g\rho_g(1-u_g) + G_{iz}\rho_{iz} + G_s\rho_s(1-u_s) + G_l\rho_l + N_{P\max}\rho_P + \dot{Q}_{kw\max}\rho_{kw}\right]$$

$$K_{TE2} = K_{el} + K_f = \frac{\rho_{el}}{\eta_P}\int_0^{\tau_P} \dot{V}_l\,\delta p(d,L)\,d\tau + (Q_A - Q_k)\frac{\rho_f}{\eta_{kw}}$$

$$K = K_{TE1} + K_{TE2}$$

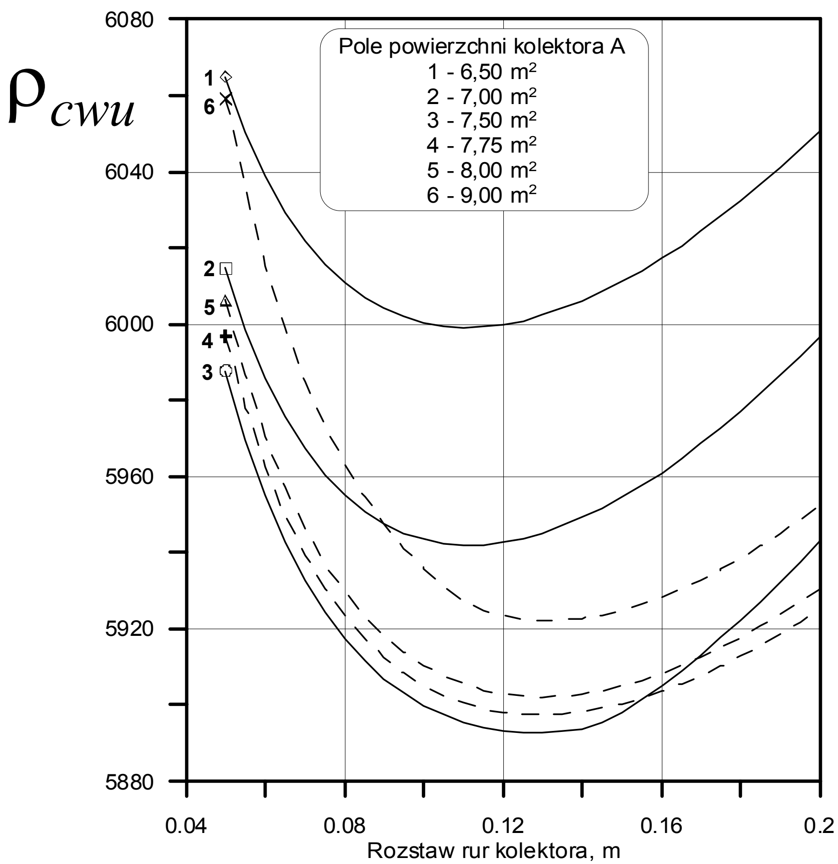
PROCEDURA OPTYMALIZACYJNA
d_{opt}, b_{opt}, A_{opt}

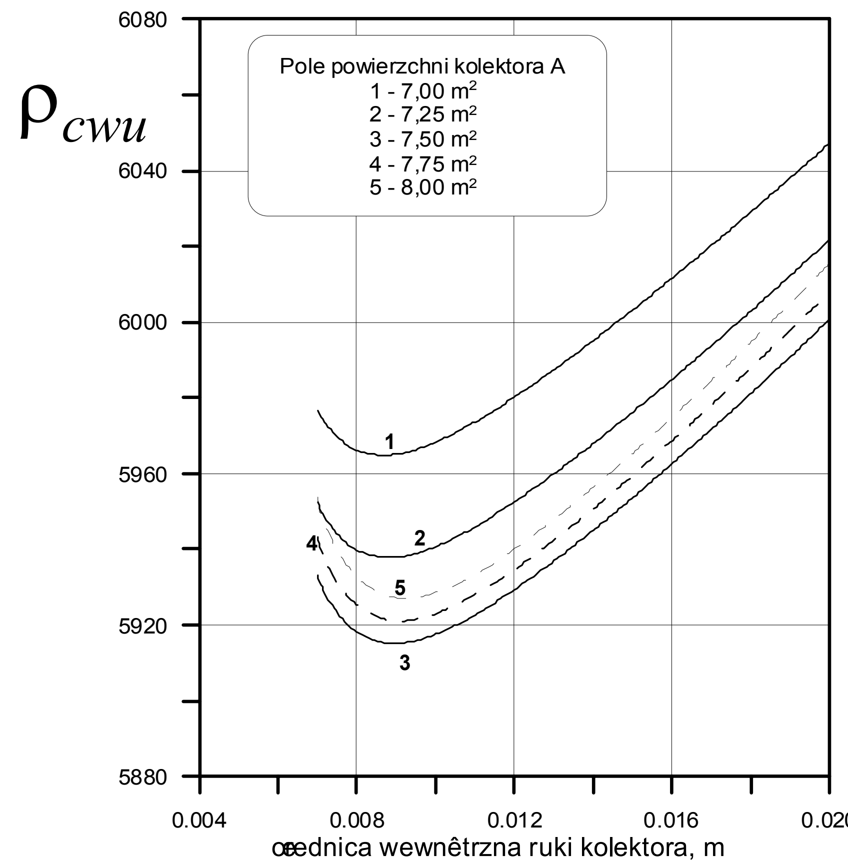
ANALIZA TE-LCA

Algorytm iteracyjny wyznaczania wskaźników kosztu termoekologicznego

Optimization of design parameters to ensure minimum depletion of natural resources - Solar colector

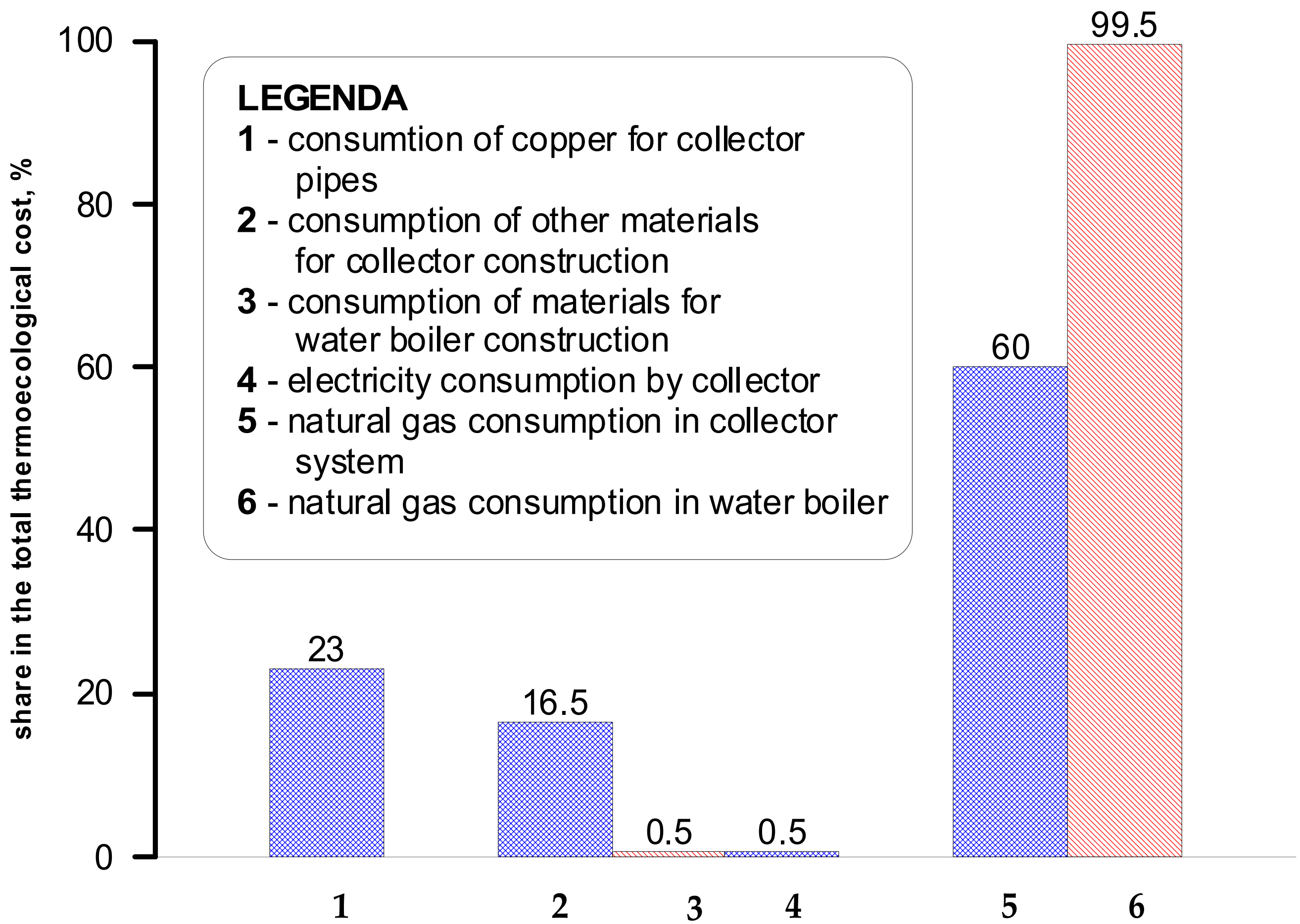
Thermo-Ecological Life Cycle Assesment



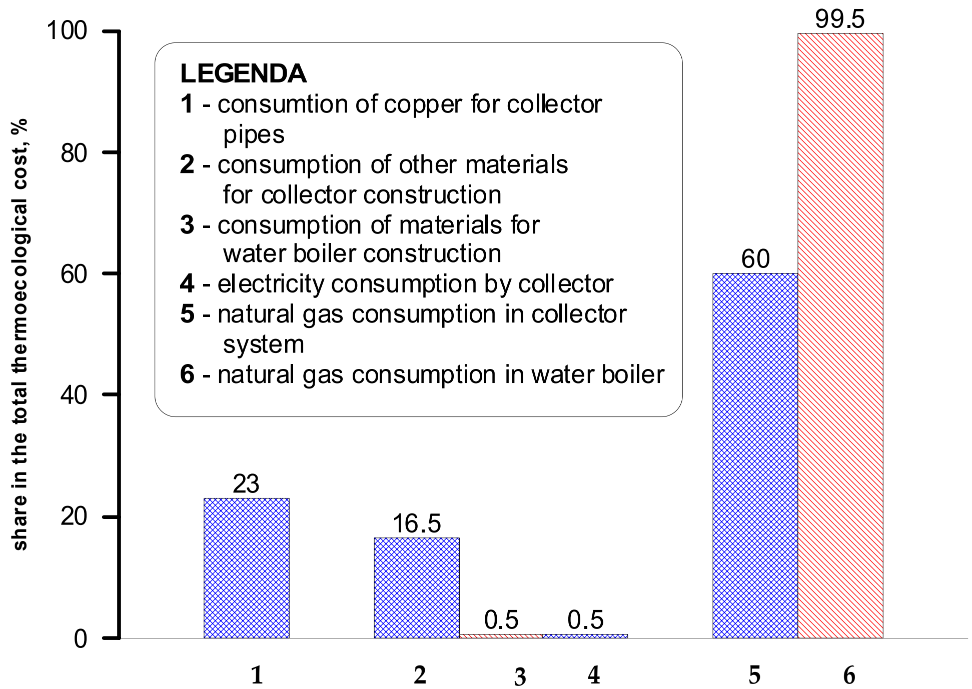


Thermo-Ecological Life Cycle Assesment

share of particular components of thermoecological cost within the life cycle of sollar collector and water boiler



Thermo-Ecological Life Cycle Assesment



in case of instalations utilising renewable energy resourcs the whole life-cycle should be taken into account when TH-cost is calculated because of significant influence of constrction phase

in case of instalations fed with fossil fuels the dominant share of TH-cost is connected with fuel consumtion (in analysed boiler 99%)

Proecological Tax

Detailed description:
Jan Szargut: *Exergy method. Technical and Ecological Applications*, WIT Press 2005

Calculation example:
Szargut J., Stanek W., ECOS'2006

Thermo-Ecological Cost Analysis Theory and Applications

Wojciech STANEK
stanek@itc.polsl.pl

Silesian University of Technology
Institute of Thermal Technology
Gliwice, POLAND

THANK YOU FOR YOUR ATTENTION