Thermo-ecological cost: an exergy-based lifecycle impact assessment – methods and applications

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Scope of the presentation

- Short academic CV
- Thermo-ecological cost (TEC)
- Examples of application of the TEC
- Pro-Ecological Tax

Short academic CV (1)

- **AGH University of Science and Technology, Faculty of Energy and Fuels, Department of Fundamental Research in Energy Engineering, Kraków, PL**

- Silesian University of Technology, Faculty of Energy and Environmental Engineering, Department of Thermal Technology, Gliwice, PL

Short academic CV (2)

Research interests:

- **Modelling and optimization** of thermal processes (2010 – present)
- Geothermal energy including **enhanced geothermal systems** (2017 – present)
- **Exergy analysis** and optimization (2012 – 2015 & 2020 – present)
- **Thermo-ecologic cost** analysis including LCA (2010 – present)
- **Techno-economic** analysis (2010 – present)
- **Carbon capture, storage and utilization** technologies (2011 – present)
- Coal-to-Nuclear and Gas-to-Nuclear **retrofits** (2020 – present)
- **Machine learning** and AI in predictive and prescriptive maintenance (2019 – present)
- **Cogeneration** technologies (2010 – 2012 & 2017 – 2020)
- Thermal engineering in **iron & steel** industry (2016 – 2020)

Thermo-ecological cost (1)

This seminar discusses the idea of **thermo-ecological cost** (**TEC**), which relies on the concept of **exergy as a measure of sustainability**. In the literature, exergy has been defined in several ways, e.g.:

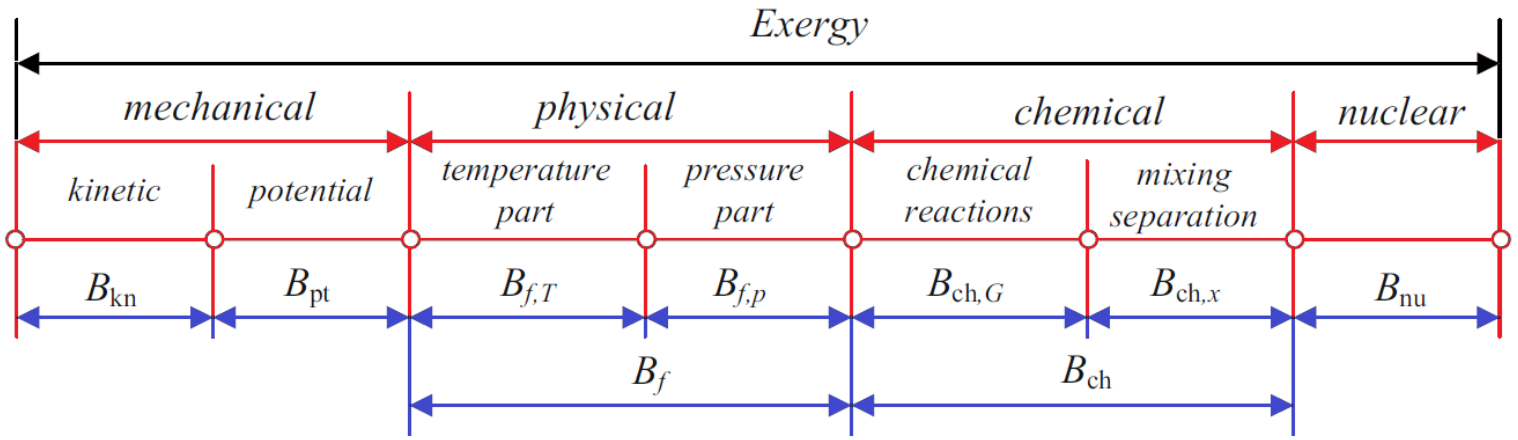
Minimal amount of work necessary to produce the investigated material with required parameters from commonly appearing components of the surrounding nature, in reversible process using the environment as a single source of heat.

Thermo-ecological cost (2)

General form of the exergy balance can be formulated as:

$$B_d + \sum B_{q,d} = \Delta B_s + \sum B_{q,w} + W + B_u + \delta B_L + \delta B_D$$

Components of general exergy balance comprise different kinds of exergy and in general can be described as:



Thermo-ecological cost (3)

The work of **Professor Jan Szargut** from the very beginning showed a broader concept of environmental protection based not only on the economy but also on thermodynamics. For the first time, Szargut proposed the term "**ecological cost**" in the **year 1978** and it was connected with a series of publications on:

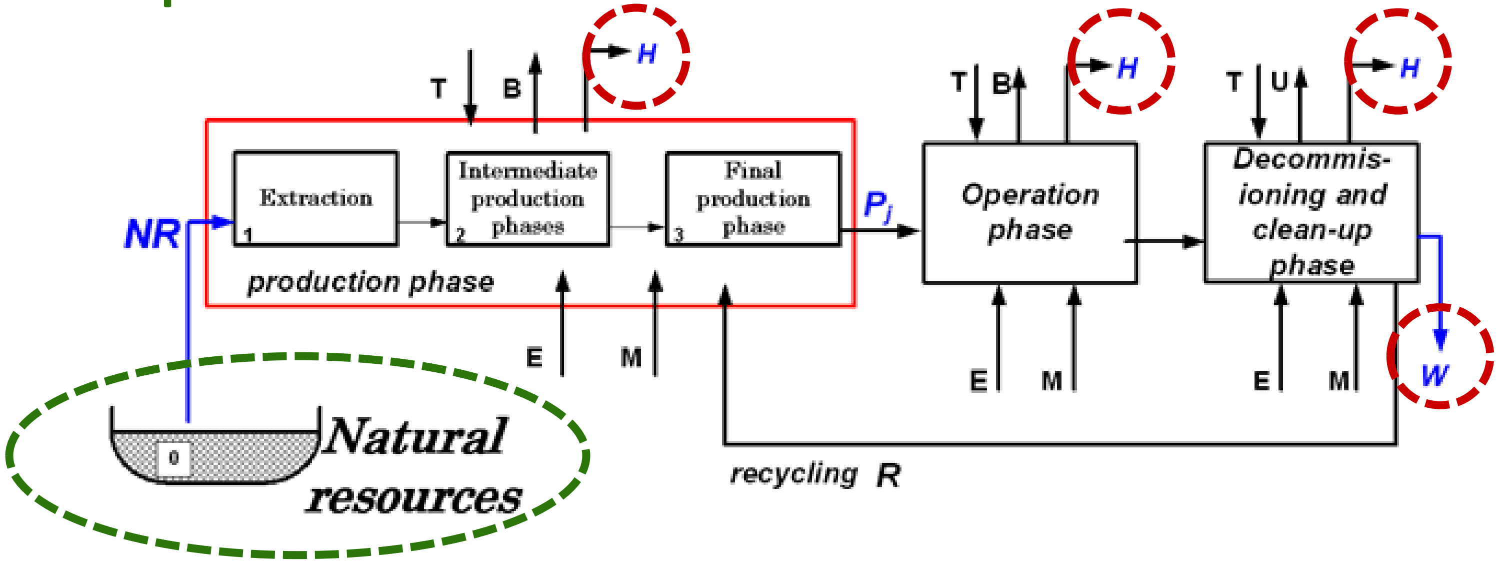
- consumption and depletion of natural resources,
- harmful pollutants and their influence on the environment,
- exergy,
- system analysis,
- ecological cost,
- cumulative energy indicators,
- cumulative exergy indicators,

from which the **Thermo-Ecological Cost** (**TEC**) methodology is derived.

Professor Jan Szargut
(09.09.1923 - 21.11.2017)

Thermo-ecological cost (4)

Manufacturing processes are interrelated, e.g. by the need for semi-finished products manufactured in other industries or transport services. The whole interconnected network of processes relies on **acquisition of resources from the nature**.

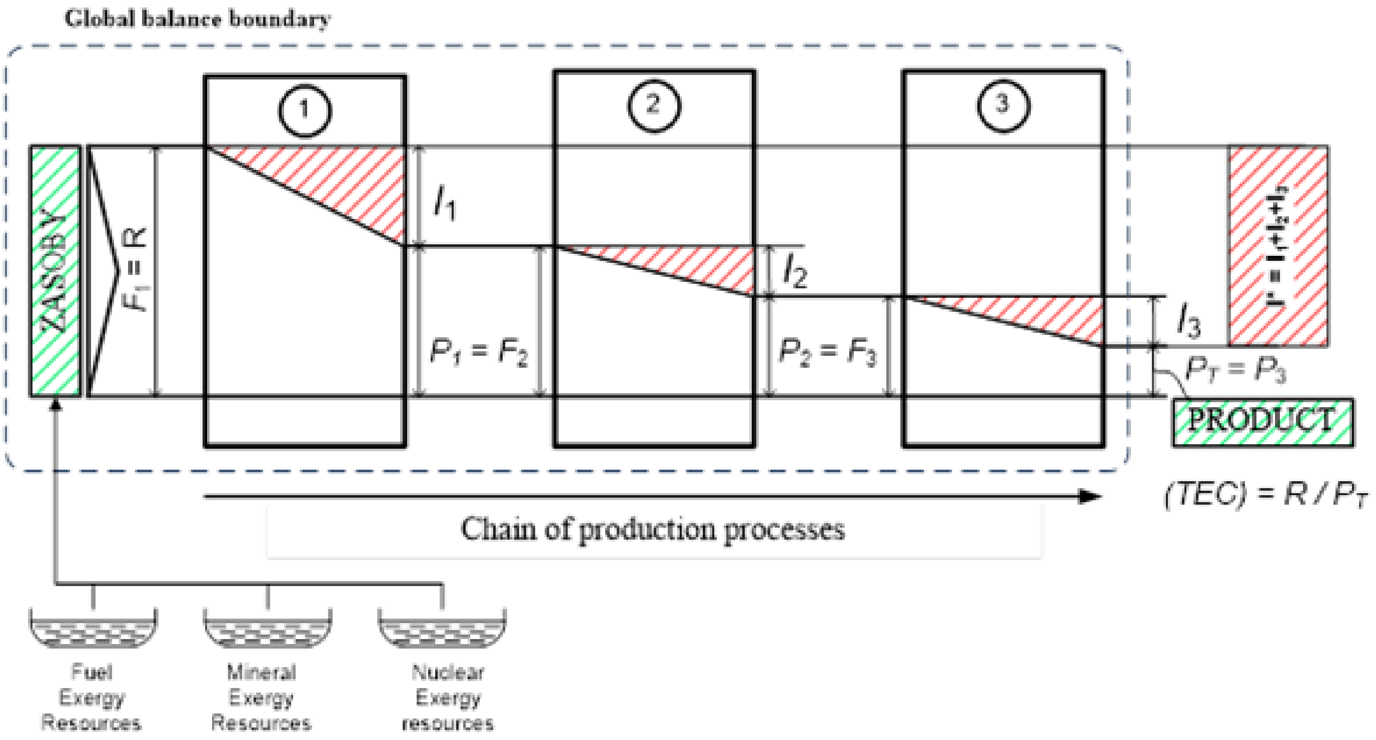


In each link in the production process network, **harmful substances may be discharged into the environment**. This discharge has **negative consequences** in the form of losses in various fields.

Thermo-ecological cost (5)

Thus, the adverse ecological effects accompanying human activities result from two groups of impacts:

1. **depletion of non-renewable natural resources consumed for production processes,**



In the method of determining the **thermo-ecological cost** developed by Professor Jan Szargut, **exergy** was adopted as **a measure of the thermodynamic quality of non-renewable resources**.

Thermo-ecological cost (6)

Thus, the adverse ecological effects accompanying human activities result from two groups of impacts:

2. **discharging harmful substances into the natural environment.**

As mentioned, this discharge has **negative consequences** in the form of losses in various fields:

- **human health** - additional demand for medicines and medical supplies;
- **industry and construction** (buildings, machinery and equipment, means of transport) - demand for products replacing damaged objects or additional demand for corrosion protection measures;
- **reduction of agricultural and forestry production**;
- **water pollution**;
- **destruction of natural ecosystems**.

Thermo-ecological cost (7)

According to the definition of Professor Jan Szargut,

*the **thermo-ecological cost** is the **cumulative consumption of exergy of non-renewable** riches that burdens **all stages of manufacturing processes**, leading from extracting raw materials from the nature to the final product. At each of the considered stages of the chain of production processes consumption of energy carriers, materials, expenditures related to transport, production of by-products and **losses associated with the discharge of pollutants into the natural environment** should be taken into account.*

Thermo-ecological cost (8)

The **main research areas of TEC analysis** include the following research topics:

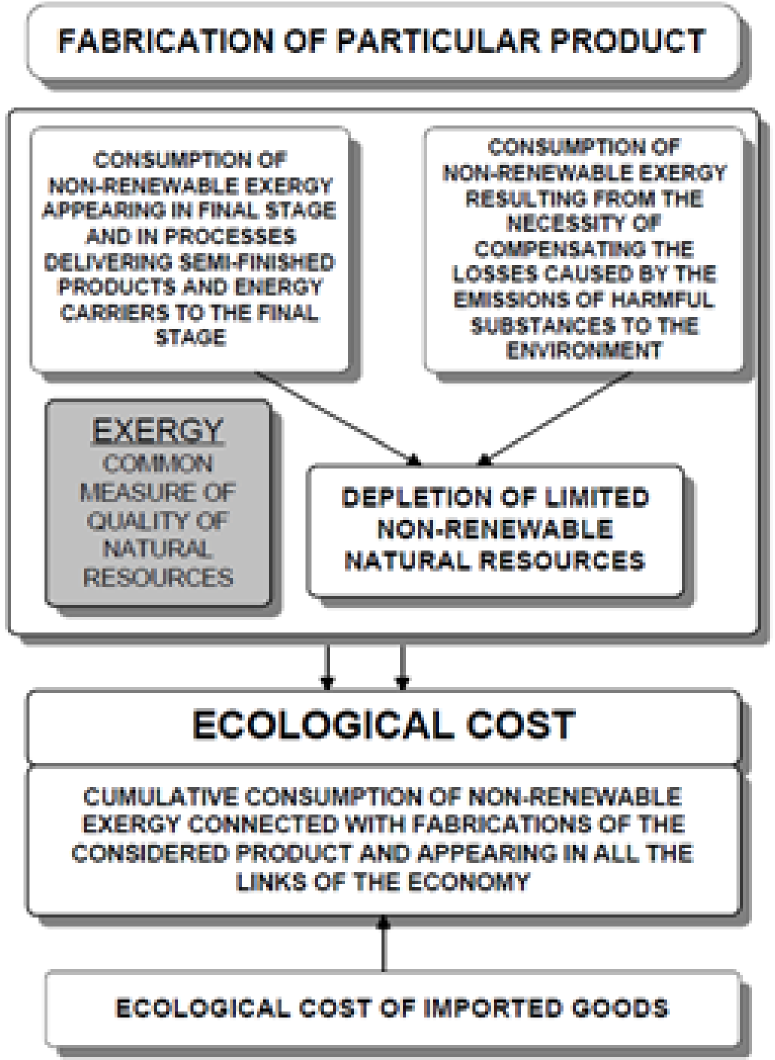
1. assessment of the impact of operational parameters of energy and manufacturing systems on depletion of non-renewable natural resources,
2. selection of production technology ensuring minimal depletion of non-renewable natural resources,
3. optimization of construction and operational parameters, in a production process of a given useful product, ensuring minimization depletion of non-renewable riches,
4. estimation of the impact of discharging harmful substances to the environment on the depletion of non-renewable resources,

Thermo-ecological cost (9)

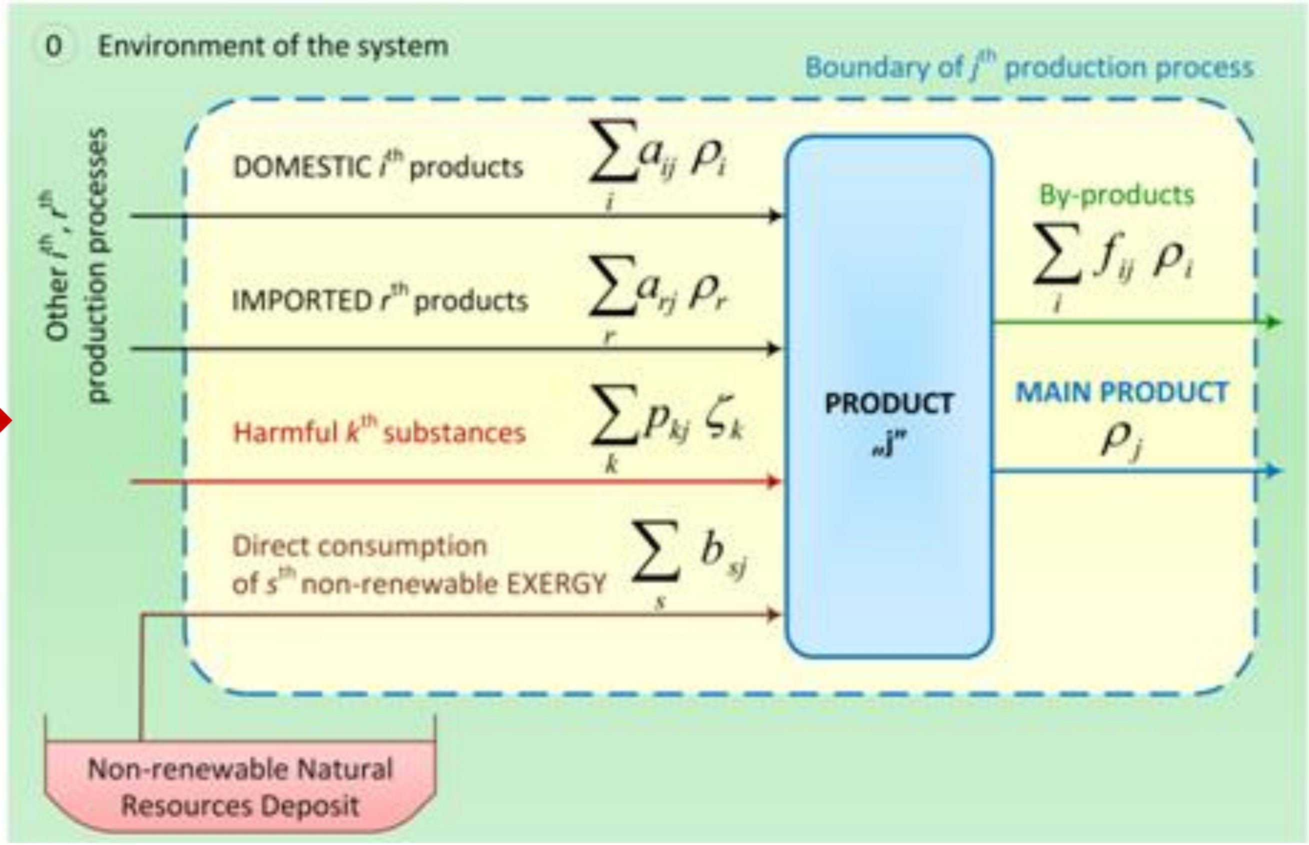
The **main research areas of TEC analysis** include the following research topics:

5. analysis of the impact of interregional exchange on the depletion of resources of national non-renewable resources,
6. determining the impact of particular useful goods on the depletion of non-renewable resources during their full life cycle (**thermo-ecological life cycle analysis**),
7. estimation of the degree of sustainable development,
8. determining the value of the **pro-ecology tax** replacing existing taxes (mainly VAT).

Thermo-ecological cost (10)



from idea to application

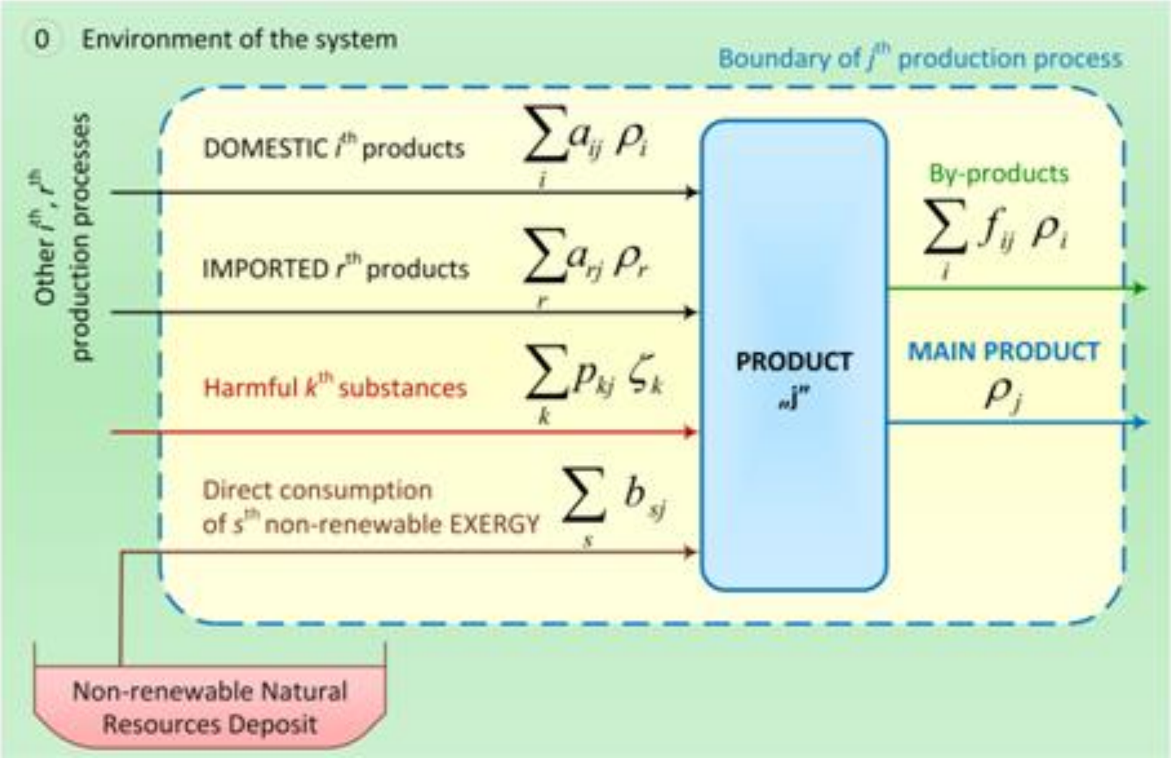


Thermo-ecological cost (11)

The idea of the **thermo-ecological cost balance** is formulated as a set of equations:

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

TEC is provided for ***j^th^* considered product**, the production of which consumes ***i^th^* domestic products**, ***r^th^* imported products**, **direct exergy of *s^th^* non-renewable resources** and releases ***k^th^* harmful substance** to the environment.



Thermo-ecological cost (12)

The **sustainability index** r_j expresses the ratio between thermo-ecological cost of the j^{th} product (from TEC balance) to its exergy, which is in inverse relation to cumulative degree of thermodynamic perfection:

$$r_j = \frac{\rho_j}{b_j}$$

*Lower value of the index of sustainability means lower cumulative consumption of exergy of natural resources per unit of exergy of particular product; consequently **lower index of sustainability is better from an ecological point of view** and future lifetime of non-renewable resources. **The index of sustainability can be lower than one only in the case of renewable energy**.*

Thermo-ecological cost (13)

Thermo-ecological evaluation of waste products

Three destruction coefficients x_{ik}, y_{ik}, z_{ik} and the p_{kj} amount of the k^{th} waste products rejected to the environment:

$$\rho_j = \sum_i (a_{ij} - f_{ij})\rho_i + \sum_r a_{rj}\rho_r + \sum_i \left[\boldsymbol{\rho_i} \sum_k (\boldsymbol{x_{ik}} + \boldsymbol{y_{ik}} + \boldsymbol{z_{ik}}) \boldsymbol{p_{kj}} \right] + \sum_s b_{sj}$$

Compensation or prevention of damage caused by the k^{th} waste product:

- to the i^{th} useful industrial or other manufactured product
- to the i^{th} agricultural or forestry product

and prevention of loss of life or health as well as to the need of treatment of people caused by the k^{th} waste product.

Thermo-ecological cost (14)

Simplified thermo-ecological evaluation of waste products

Simplified thermo-ecological cost of waste products can be defined as:

$$\zeta_k = \frac{B^E w_k}{GDP - \sum_k P_k w_k}$$

where:

B^E – total annual exergy extraction (production) of non-renewable natural resources,

GDP – gross domestic product

w_k – total rate of losses in the environment burdening the k^{th} substance discharged into the environment (expressed in **monetary units** per unit of k^{th} substance)

Thermo-ecological cost (15)

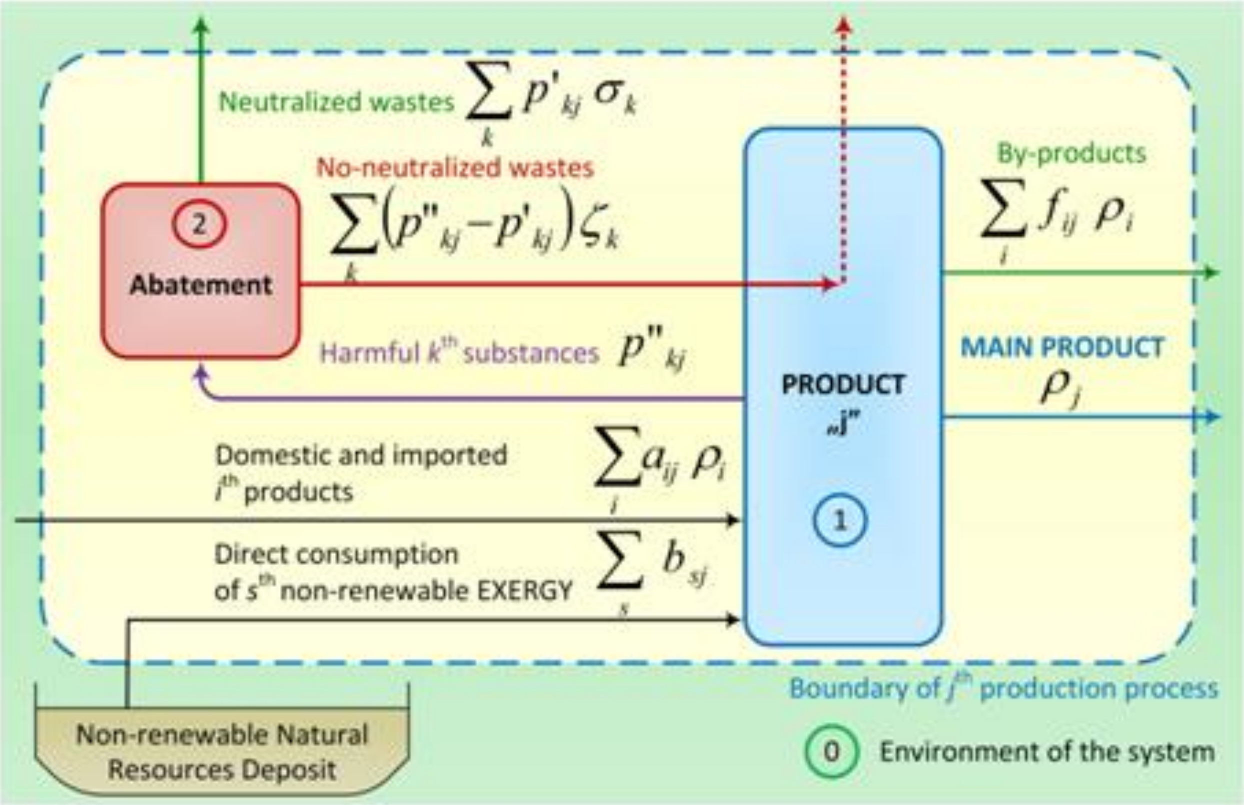
Thermo-ecological cost of abatement installation

Often there is a need of modifying an ecological cost based on harmfulness coefficients by splitting the main installation and the abatement installation, and hence, expenses of cumulative exergy of non-renewable resources (σ_k) caused by the neutralization of some pollution are isolated.

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

where

$$p_{kj} = p''_{kj} - p'_{kj}$$



Thermo-ecological cost (16)

Thermo-ecological cost of abatement installation

Abatement of harmful substances should require less cumulative exergy of non-renewable resources **than** is necessary **to compensate for the losses** caused by rejection of this harmful effluent directly to the environment without purification. The higher is the difference between the exergy cost of environmental losses and the exergy cost of the life cycle of the abatement installation, the more justified is such abatement.

$$r_k = \frac{\sigma_k}{\zeta_k}$$

This ratio („**environmental sustainability index**”) of the exergy cost resulting from the life cycle of the removal installation to the exergy cost of environmental losses should be much lower than 1 as far it is justified from an economical point of view.

Thermo-ecological cost (17)

Thermo-ecological cost of abatement installation

Indicator	Unit	Substance			
		SO_2	NO_x	Dust	CO_2
ζ_k	MJ_{ex}/kg	97.8	71.9	53.4	–
σ_k	MJ_{ex}/kg	17.5	26.0	0.5	4.4
r_σ	–	0.18	0.36	0.01	–

In each case the value of r_σ is smaller than unity. In relation to the chosen criterion, dust extraction is particularly advantageous. For this technology, the r_σ index reaches a value of 0.01. This is reflected in the widespread use of dust extraction.

Thermo-ecological cost (18)

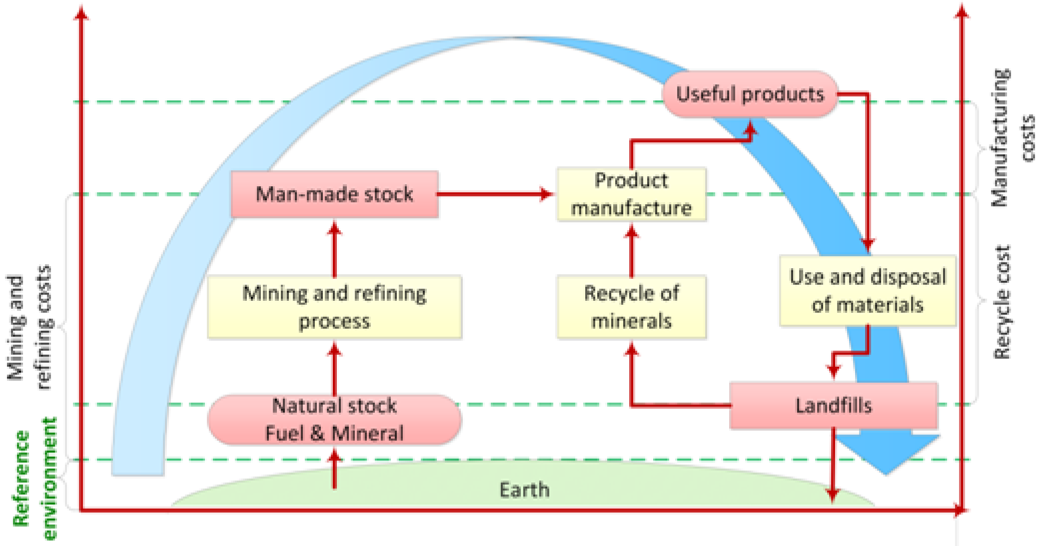
Lifetime in thermo-ecological cost methodology

From the very beginning the thermo-ecological cost is a generalization of the currently most applied LCA methodology.

Thermo-ecological cost in life cycle (**TEC-LC**) can be expressed by:

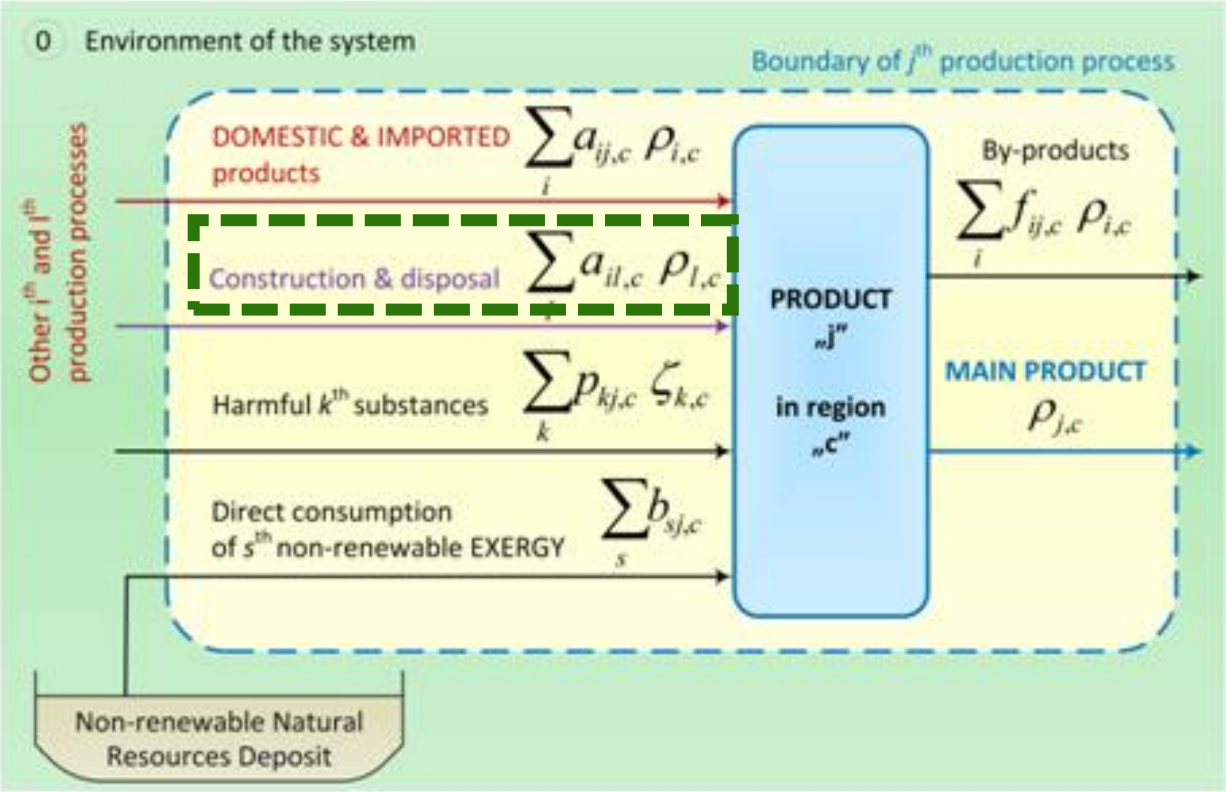
$$\rho_{j,c} = \sum_i (a_{ij} - f_{ij})\rho_{i,c} + \sum_l a_{lj}\boldsymbol{\rho_{l,c}} + \sum_k p_{kj}\zeta_{k,c} + \sum_s b_{sj}$$

thermo-ecological cost connected with the l^{th} investment and dismantling phase of the product in c^{th} region, e.g. MJ/kg



Thermo-ecological cost (19)

Lifetime in thermo-ecological cost methodology



Thermo-ecological cost (20)

By-products in thermo-ecological cost methodology

As in all environmental assessments it is difficult to clearly determine which part of the cost burdens either the main product or by-product of the associated process.

Production process / Plant	Main product	By-product	Replaced product
Heat and Power Plant	Steam heating	Electricity	Electricity generated in condensing power plants
Coking, the coking process	Coke	Coke oven gas	Flammable gas
Steelworks, the blast furnace process	Pig iron	Blast furnace gas	Flammable gas

Thermo-ecological cost (20)

By-products in thermo-ecological cost methodology

The basic balance equation, which considers the by-products according to principles of avoiding expenditure, changes into:

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

coefficient of production of the u^{th} by-product per unit of the j^{th} main product, in unit of u^{th} by-product per unit j^{th} product e.g. kg/kg

thermo-ecological cost of u^{th} considered by-product, in MJ of exergy per unit of u^{th} considered by-product e.g. MJ/kg.

Example for cogeneration and polygeneration processes

Thermo-ecological cost (21)

Fuel part and mineral part of the thermo-ecological cost

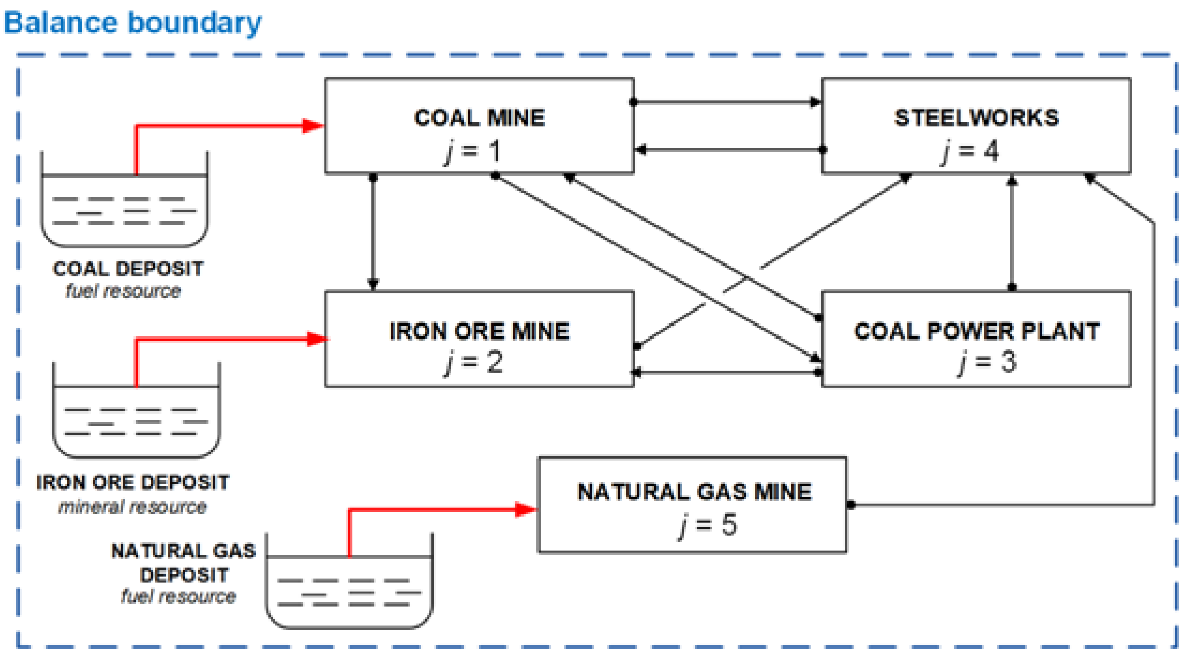
The TEC indicates negative impacts of **fuels and minerals mining**; for this reason, the **natural resource part of thermo-ecological balances could be split into two parts**, namely **fuel** and **mineral** ones, in order to distinguish their contribution.

$$\rho_j = \sum_i (a_{ij} - f_{ij})\rho_i + \sum_r a_{rj}\rho_r + \sum_k p_{kj}\zeta_k + \sum_f \boldsymbol{b_{fj}} + \sum_m \boldsymbol{b_{mj}}$$

exergy of the fuel and of the mineral raw material immediately extracted from nature, per unit of the j^{th} major product

Thermo-ecological cost (22)

Fuel part and mineral part of the thermo-ecological cost



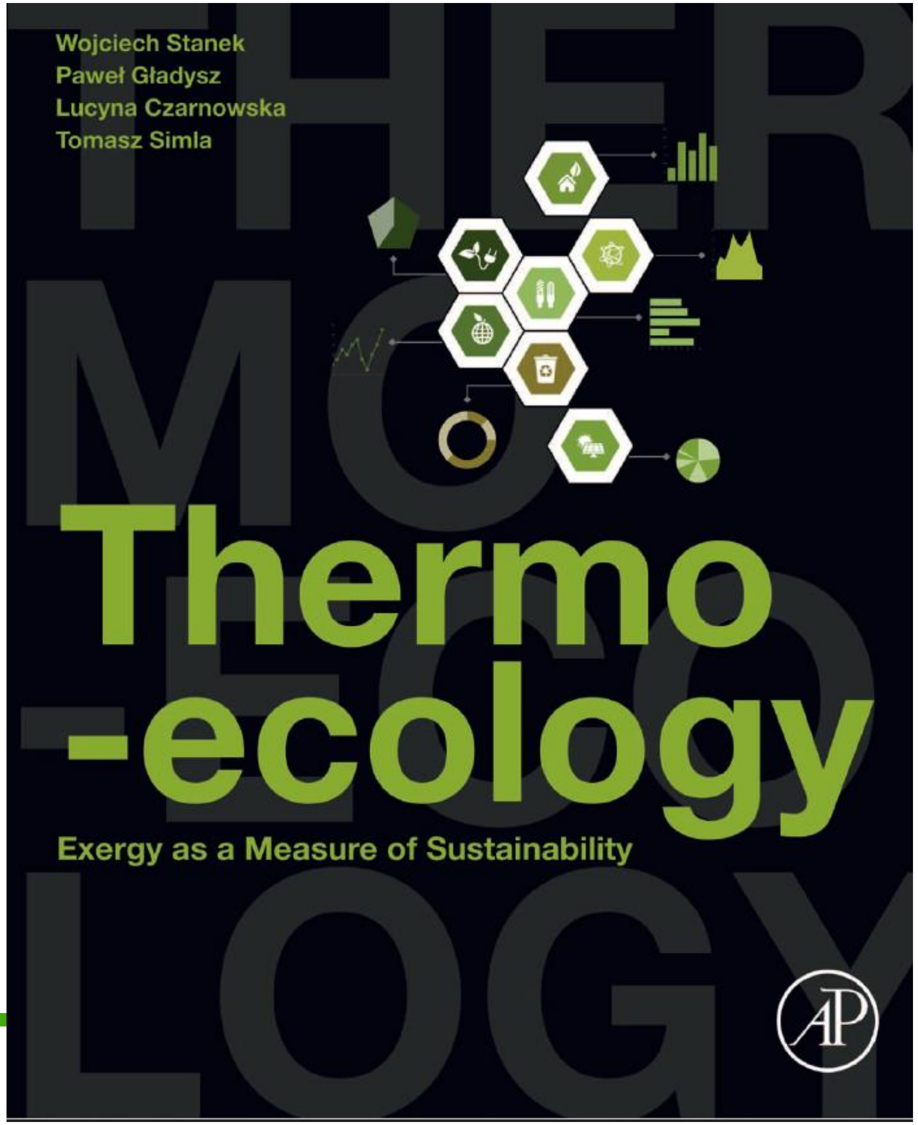
		j – component of the system				
		1	2	3	4	5
		kg	kg	MJ	kg	kmol
Product i **a_{ij}** **[i]/[j]**	$i = 1$	–	0.001	0.137	0.410	–
b_j, MJ/[j]		26.16	0.80	0.00	0.00	809.43
ρ_j, MJ/[j]		30.96	1.33	4.78	30.23	829.36
r_j		1.18	1.66	4.78		1.03
z_j, %		99.49	37.82	99.54	95.81	99.99

fraction of the fuel part of the considered quantity

Thermo-ecological cost (23)

More on:

- Thermo-ecological simplified evaluation of imported and exported products
- Extended thermo-ecological evaluation of imported and exported products
- Human labour in thermo-ecological cost methodology
- Developed and extended concept of thermo-ecological cost
- Partial thermo-ecological cost
- TEC-LC of mineral and metal extraction
- …



TEC examples (1)

TEC-LC of hard coal in selected countries

Motivation: Determination of the appropriate value of fuels has a huge impact on the TEC-LC, since the fuel part has the largest share in the total results of TEC-LC of almost all products.

Region	LHV	Exergy of raw coal	TEC-LC (extraction)	TEC-LC (loco users)
Units	MJ/kg	MJ_{ex}/kg	MJ_{ex}/kg	MJ_{ex}/kg
AU	20.1	21.91	30.66	30.89
CPA and China	19.7	21.47	24.16	24.39
EEU	16.1	17.55	24.41	24.75
RLA	19.1	20.82	26.46	26.69
RNA	16.1	17.55	23.58	24.16
RU	17.3	18.86	24.09	24.49
WEU	15.8	17.22	26.82	26.97
ZA	20.1	21.91	28.87	29.31

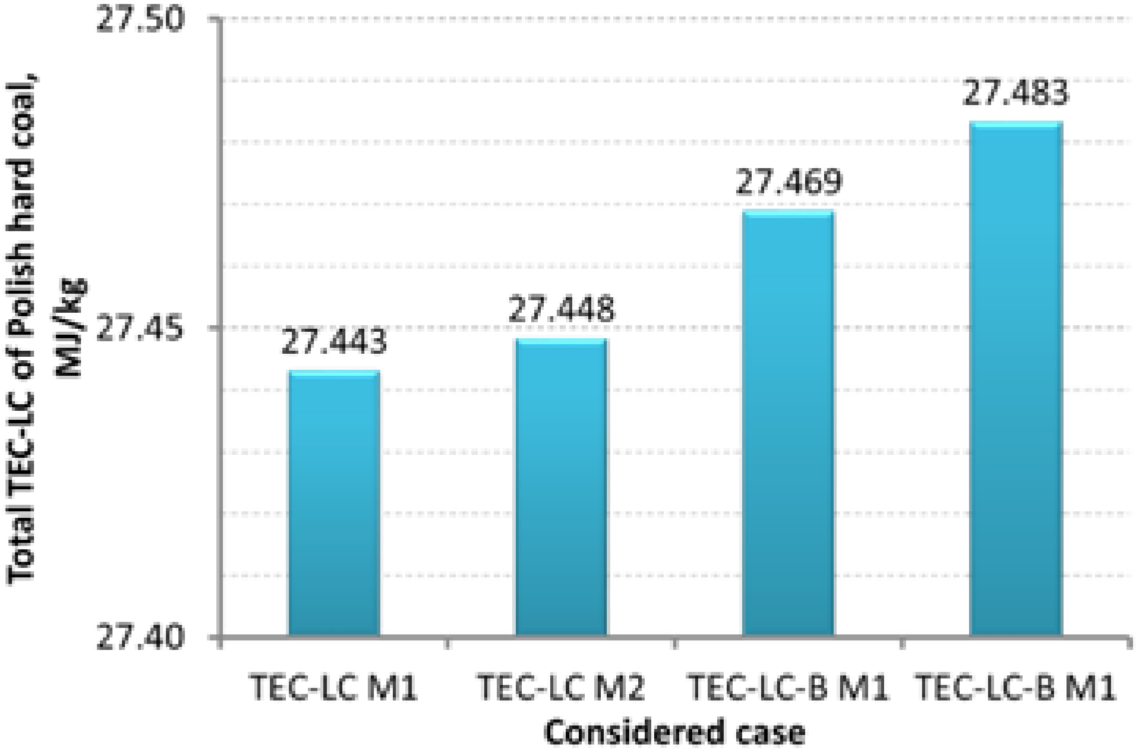
TEC examples (2)

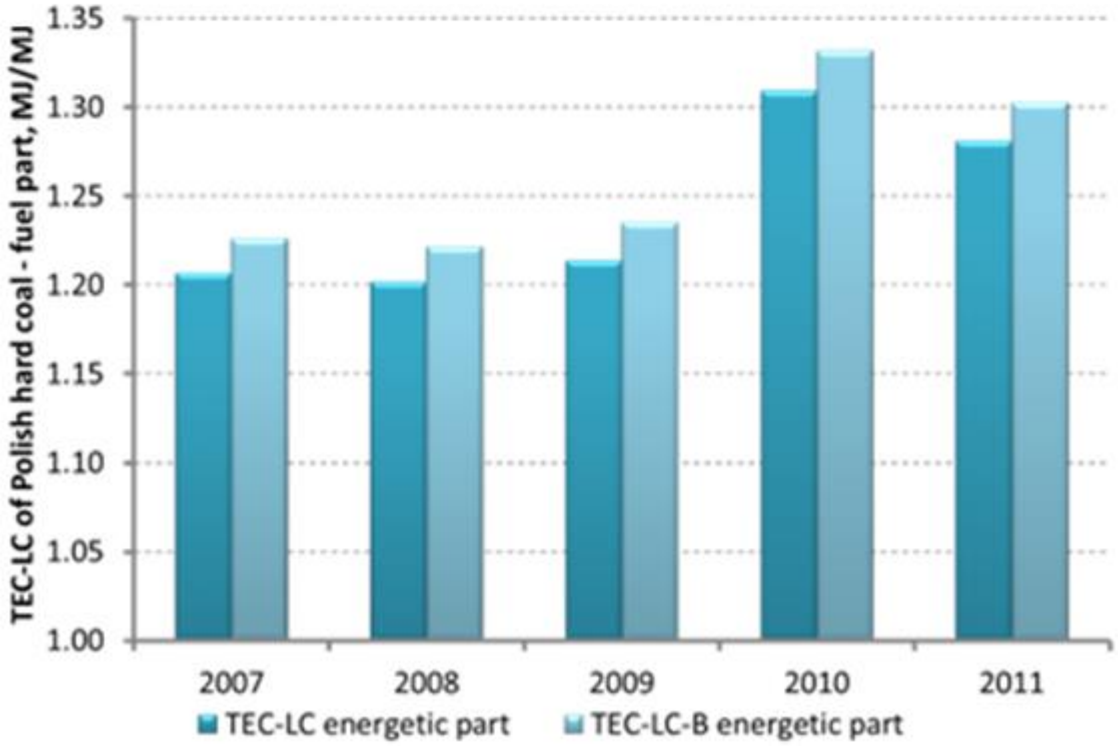
Motivation: Determination of the appropriate value of fuels has a huge impact on the TEC-LC, since the fuel part has the largest share in the total results of TEC-LC of almost all products.

Country ID	$\rho^{f}_{j,c}$	$\rho^{m}_{j,c}$	$\rho^{k}_{j,c}$	Total TEC-LC $\rho_{j,c}$
Units	MJ_{ex} /kg	MJ_{ex}/kg	MJ_{ex}/kg	MJ_{ex}/kg
US	24.384	0.026	0.212	24.622
CZ	24.735	0.014	0.165	24.914
PL	24.768	0.015	0.159	24.942
SK	25.056	0.025	0.208	25.289
HR	25.128	0.027	0.174	25.329
AT	25.227	0.028	0.158	25.414
DE	27.543	0.016	0.186	27.745
ES	28.201	0.019	0.271	28.491
IT	28.568	0.026	0.403	28.998
PT	28.923	0.023	0.369	29.315
FR	29.787	0.029	0.453	30.269

TEC examples (3)

Average thermo-ecological cost-life cycle (TEC-LC) of Polish hard coal in 2007-2011

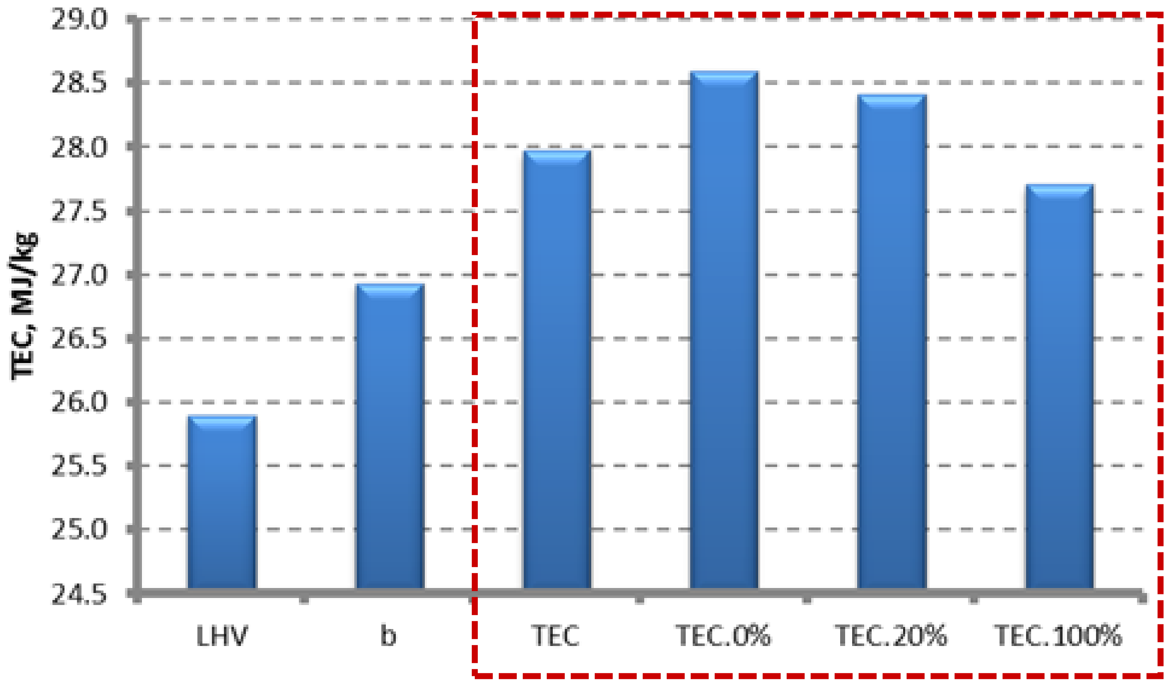




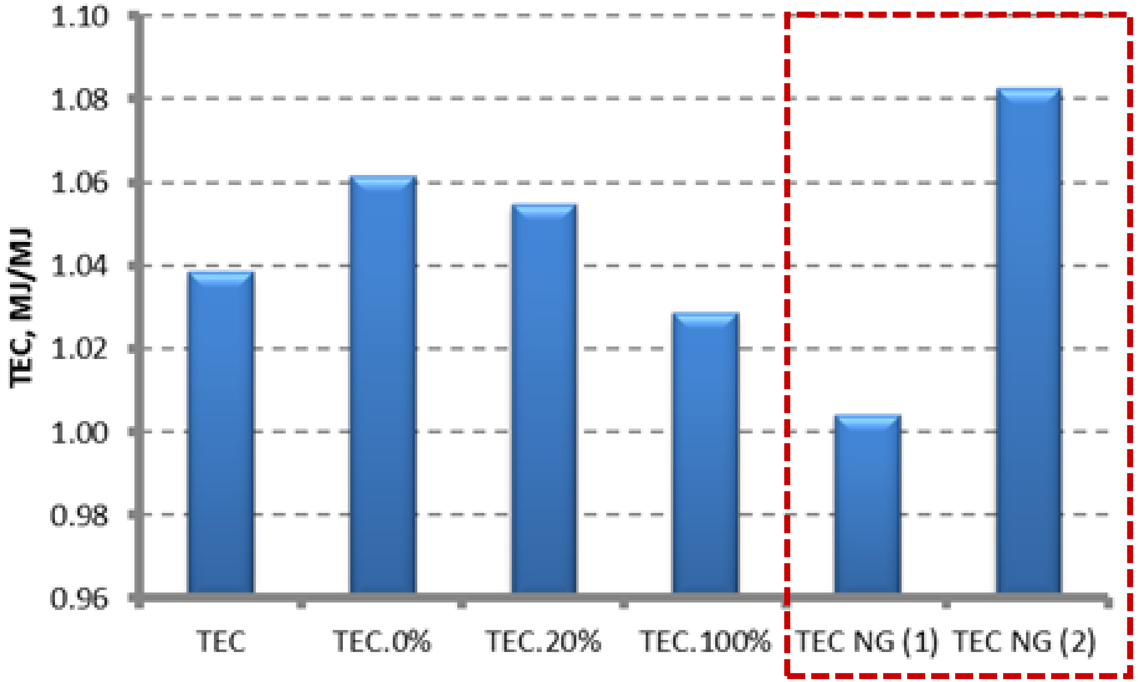
TEC examples (4)

Average thermo-ecological cost-life cycle (TEC-LC) of Polish hard coal

TEC of coal with different degree of methane utilization



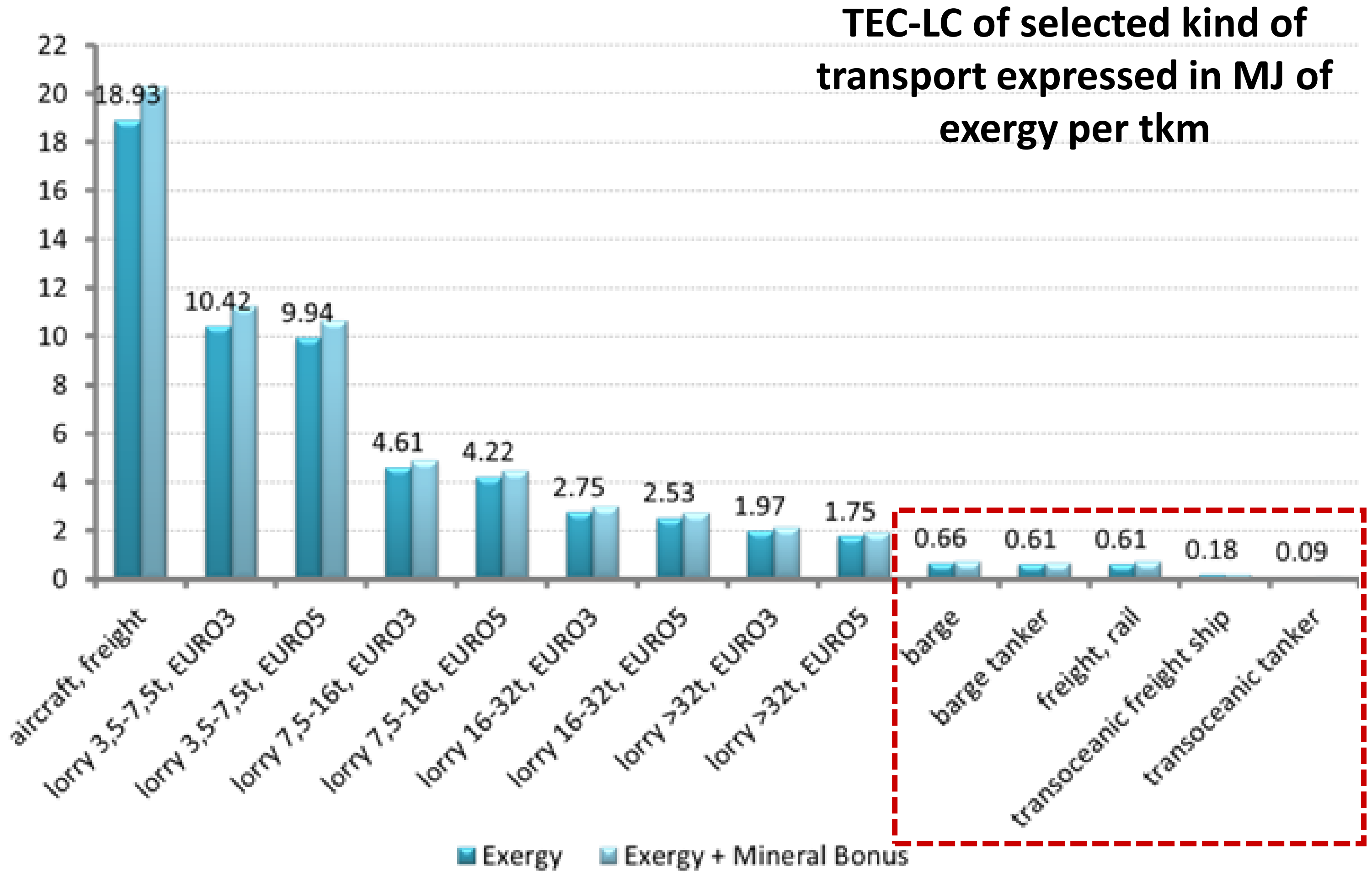
TEC of coal in comparison with natural gas



TEC examples (5)

TEC-LC of transport

Motivation: Currently, human life is dependent substantially on various means of transport.

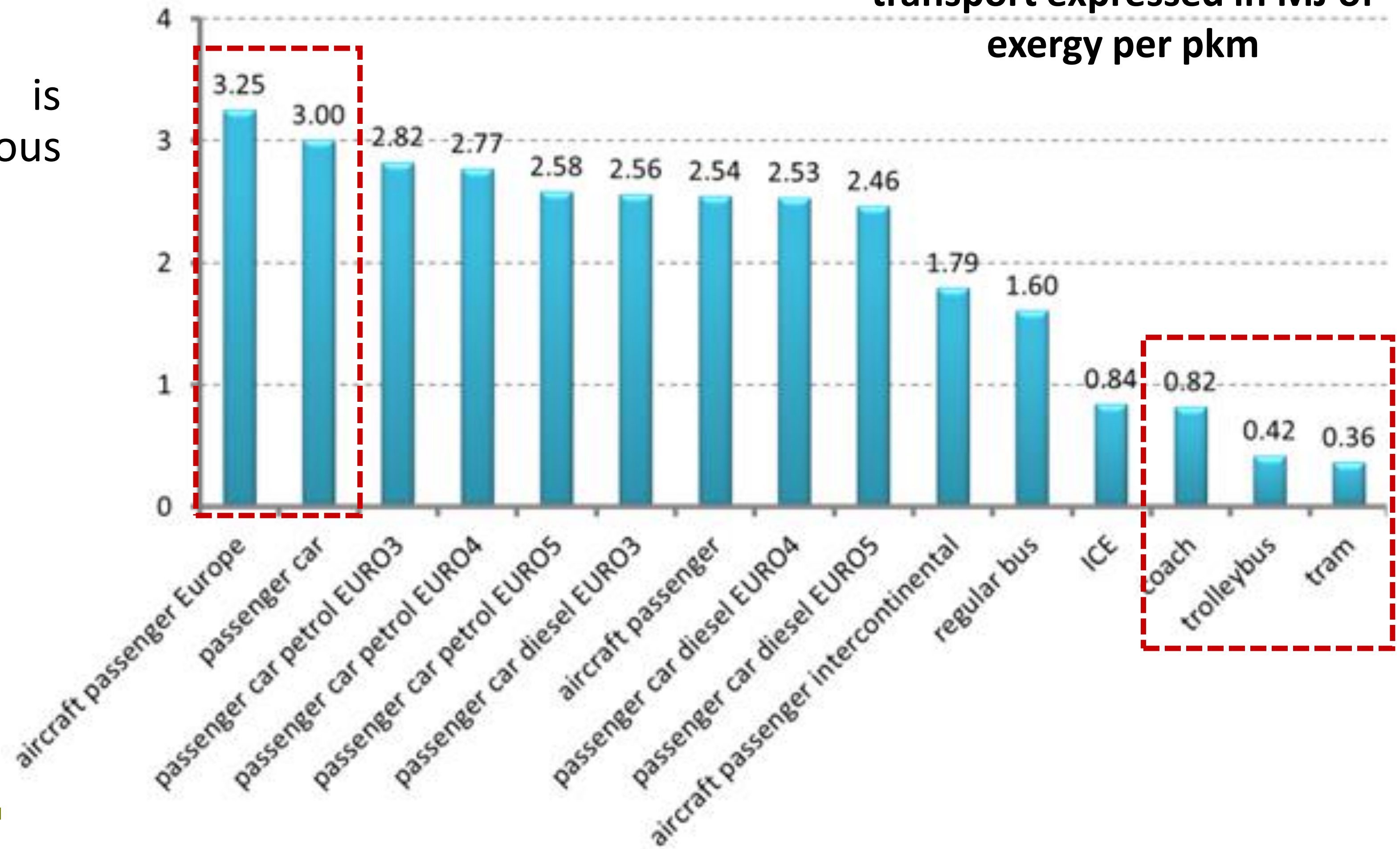


TEC examples (6)

TEC-LC of transport

Motivation: Currently, human life is dependent substantially on various means of transport.

TEC-LC of selected kind of transport expressed in MJ of exergy per pkm

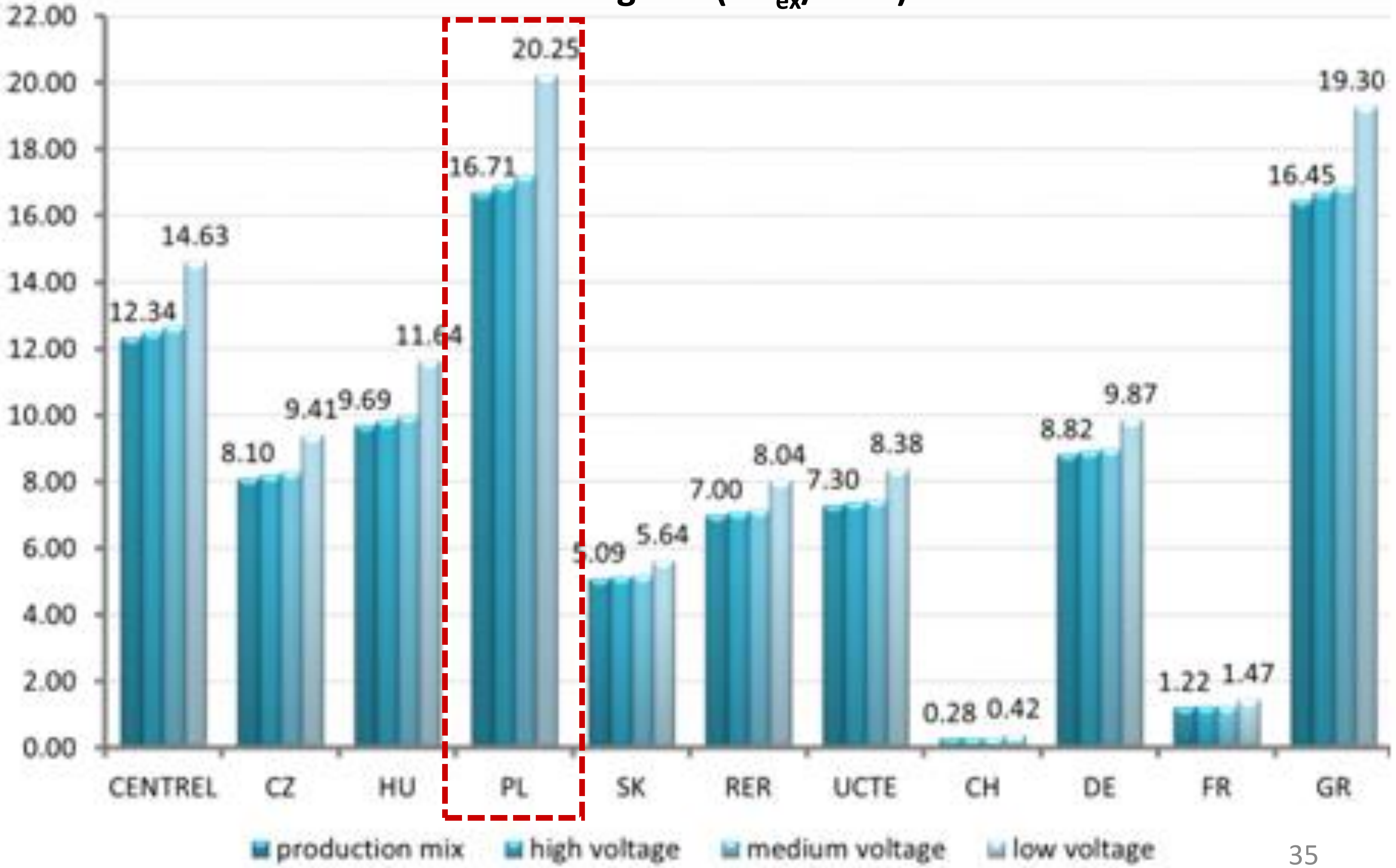


TEC examples (7)

TEC-LC of electricity in selected regions

Motivation: The TEC-LC of electricity production mix and transmission through the high voltage, medium voltage and low voltage transmission lines in the selected countries and regions is essential for comaprision studies.

Thermo-ecological cost-life cycle of electricity in selected regions (MJ_{ex}/kWh).

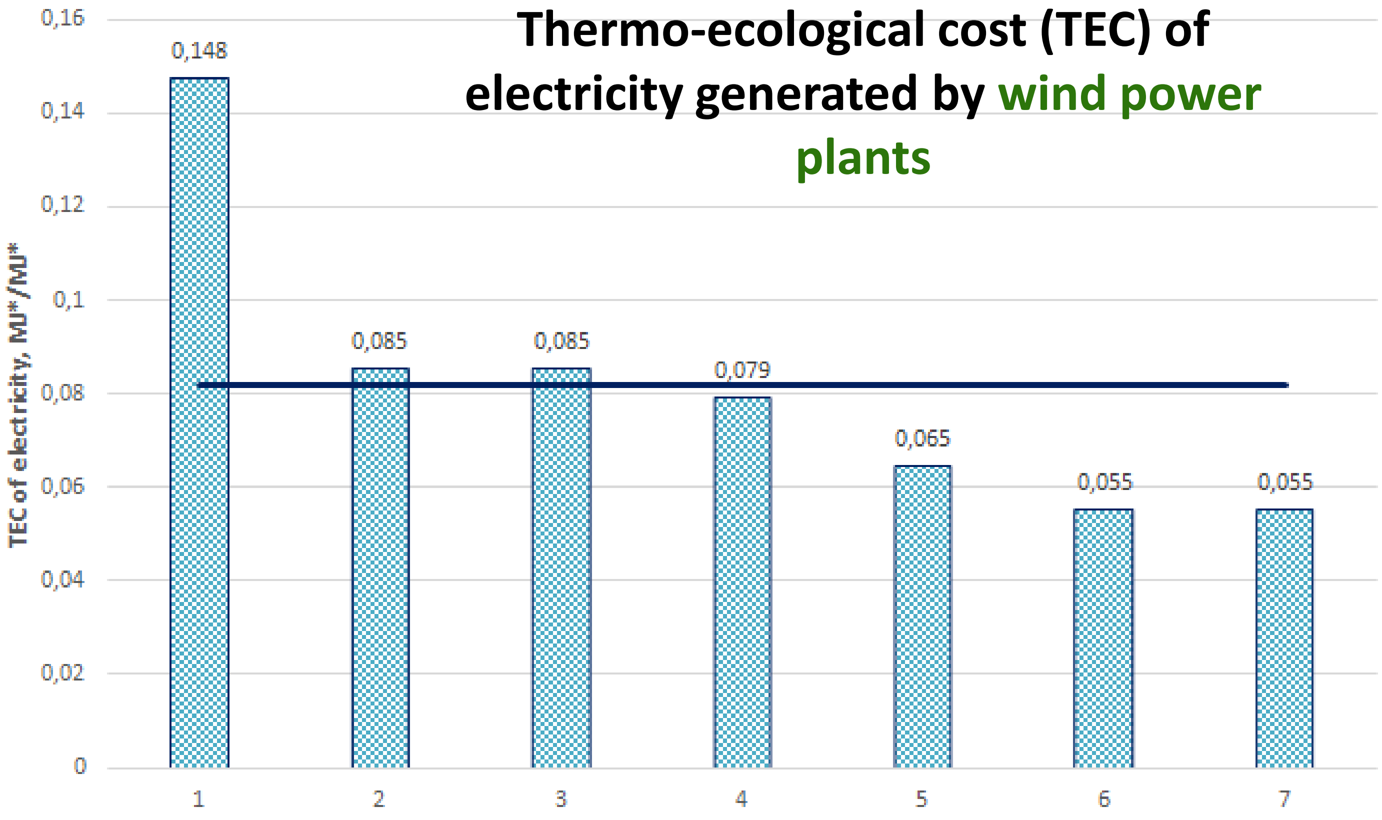


TEC examples (8)

Thermo-ecological cost of renewable fuels

Motivation: TEC calculations based on the data of various RES installations in the European Union are provided for comparative studies.

1. Grenchenberg 150 kW power plant in Switzerland;
2. 600 kW power plant in Switzerland;
3. Average in the Oceanic region;
4. 800 kW power plant in Switzerland;
5. 2 MW offshore power plant;
6. Average in Switzerland;
7. Average in Europe.

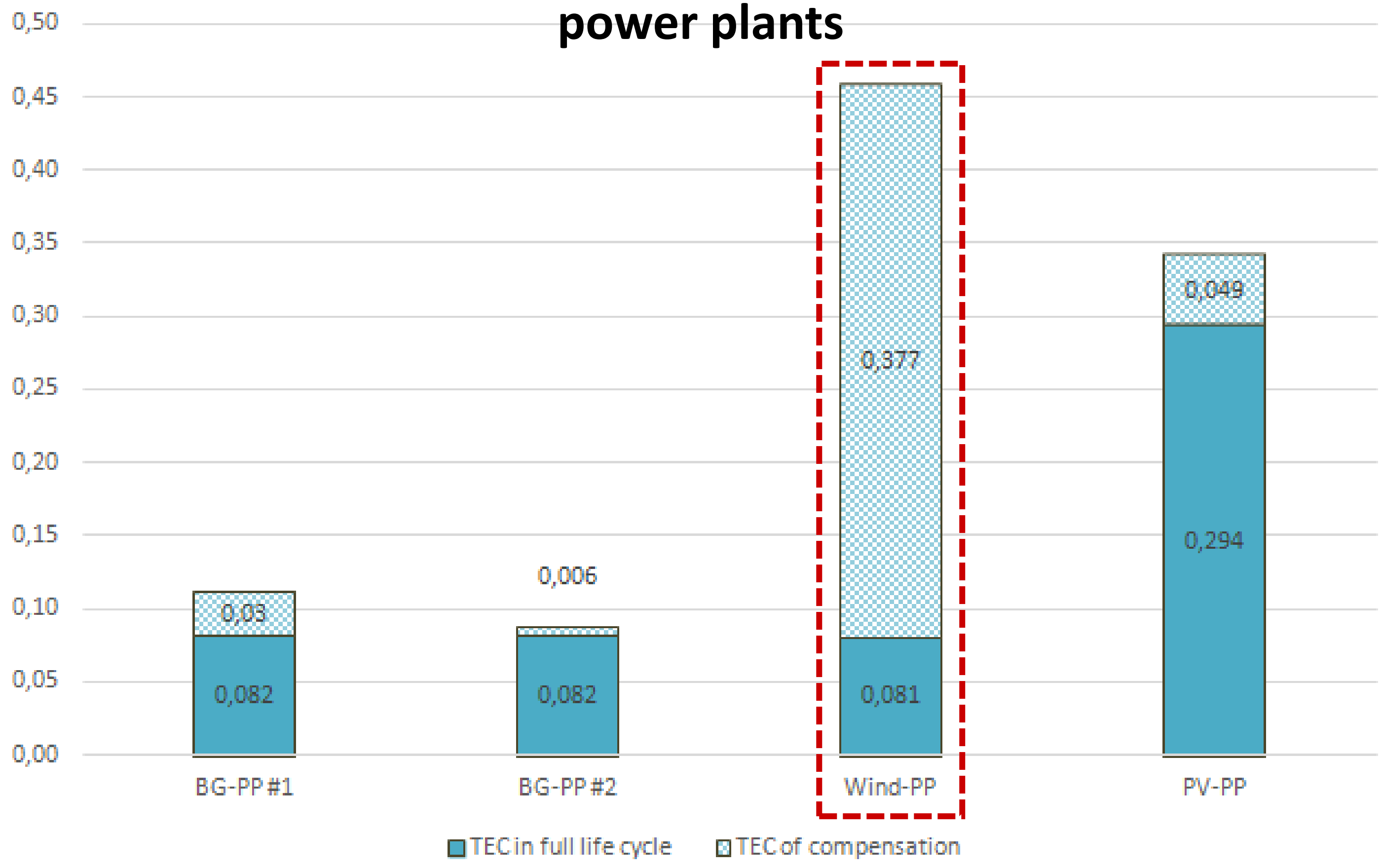


TEC examples (9)

Thermo-ecological cost of renewable fuels

Motivation: Having in mind the data characterizing random accessibility of renewable technologies it is necessary to extend the **TEC approach by losses resulting from the compensation of random operation of renewable technologies**.

TEC of electricity from analysed RES power plants

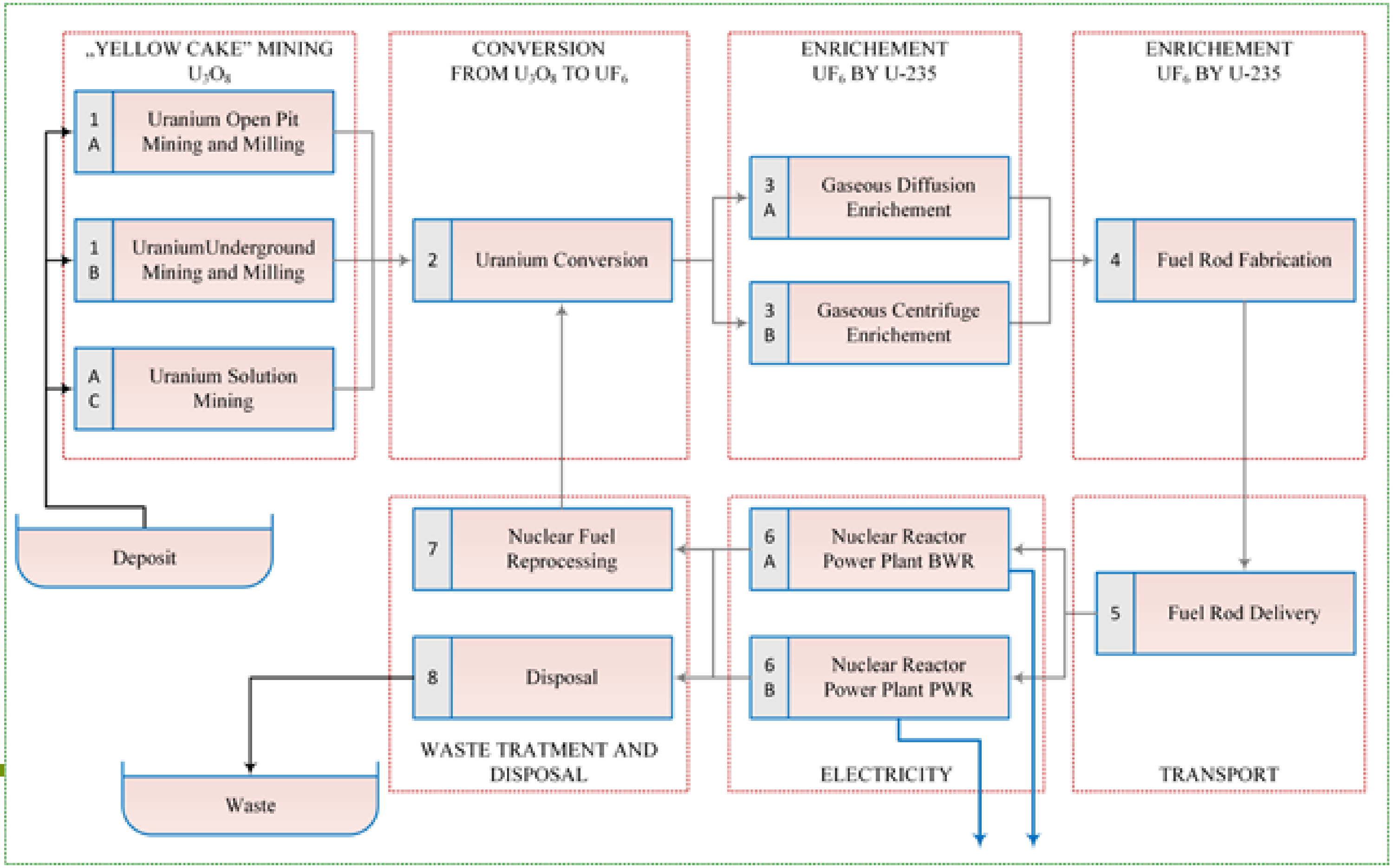


TEC examples (10)

Thermo-ecological evaluation of nuclear power plant within the whole life cycle

Motivation: Comparison of nuclear power plant with coal-fired plants requires an evaluation within the whole life cycle and application of a common measure of the consumption of natural resources.

The whole cycle of nuclear technology



TEC examples (11)

Thermo-ecological evaluation of nuclear power plant within the whole life cycle

Motivation: Comparison of nuclear power plant with coal-fired plants requires an evaluation within the whole life cycle and application of a common measure of the consumption of natural resources.

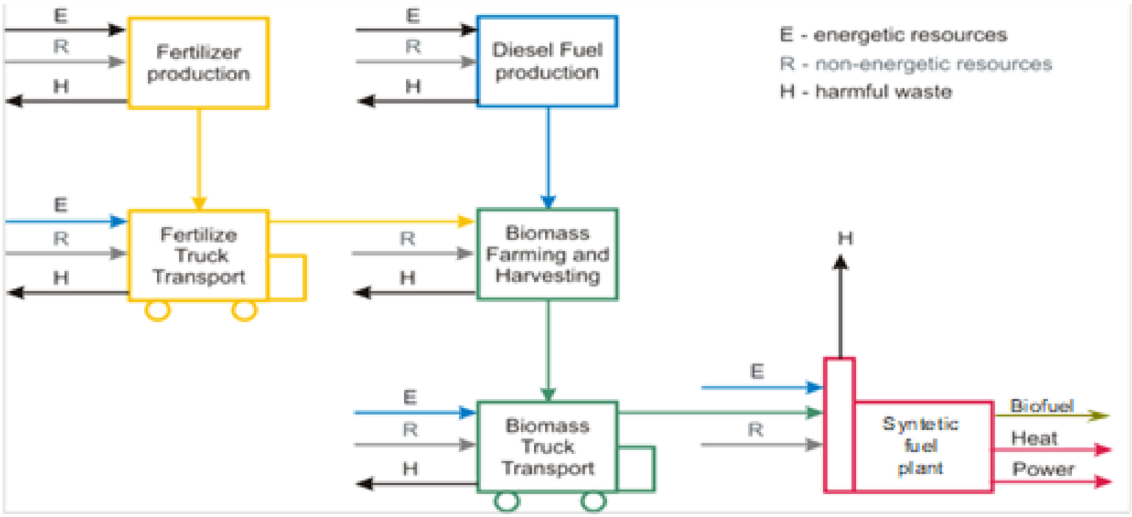
Power plant	Local exergy efficiency $\eta_{B,el}$, %	$(TEC)_{LCA}$ MJ^*/MJ_{el}	System exergy efficiency $\eta^*_{B,el}$, %
Nuclear existing	24.1	**58.39**	1.71
Nuclear Gen III +	41.3	**34.13**	2.93
Nuclear existing (recycling)	27.0	**57.80**	1.73
Nuclear GEN III+ (recycling)	46.2	**33.78**	2.96
Coal average in Poland	31.8	**3.90**	25.64

Processes of fuel conversion and enrichment have a dominant influence on high exergetic cost of the whole nuclear chain.

TEC examples (12)

Thermo-ecological cost evaluation of biofuels

Motivation: The methodology of TEC-LCA can be applied to the analysis of the biomass-to-biofuel conversion proces to assess tchem in comprehensive manner.

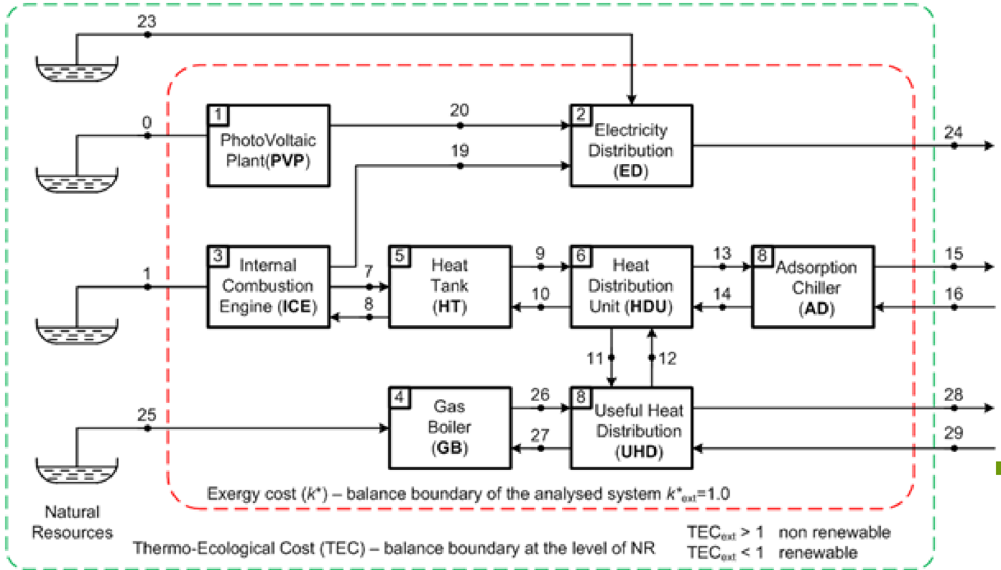


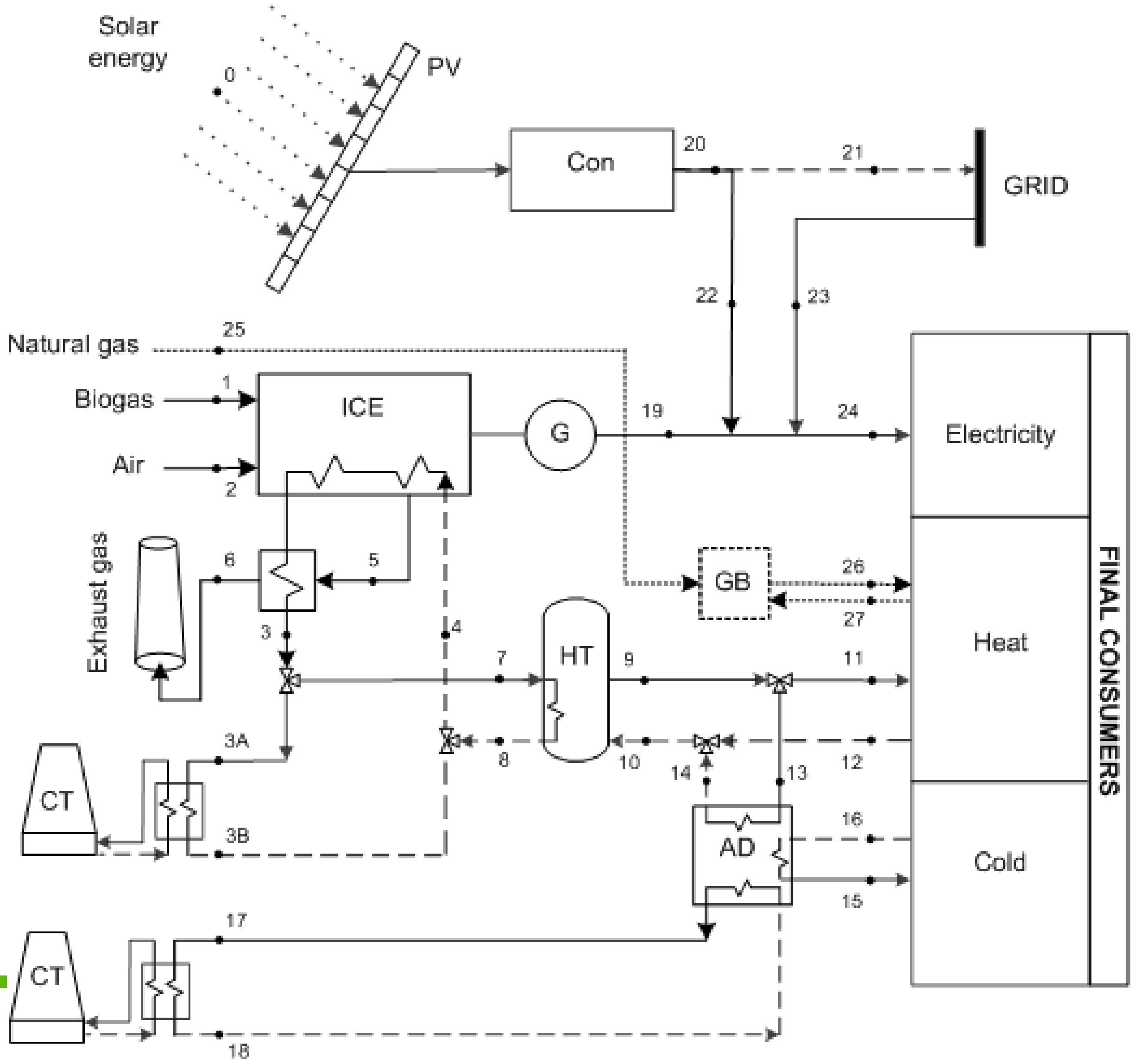
No.	Unit	FT fuels	Methanol	Hydrogen	SNG
Case 1 (PL mix)	MJ/MJ	0.232	3.52	0.627	0.989
Case 2 (RES only)	MJ/MJ	0.232	0.328	0.232	0.135

TEC examples (13)

Thermo-ecological assessment of CCHP plant supported with renewable energy

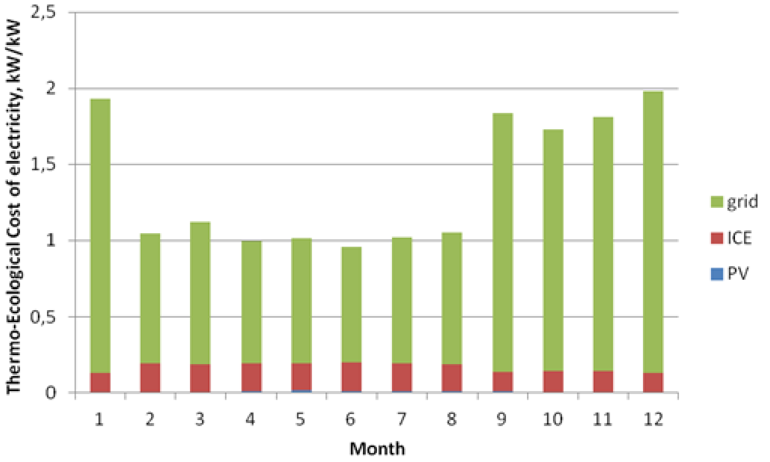
<u>Motivation</u>: The current energy policy requires a constant technology development toward more sustainable energy transformation systems, including trigeneration systems (e.g. combined cold-heat-and-power plants).

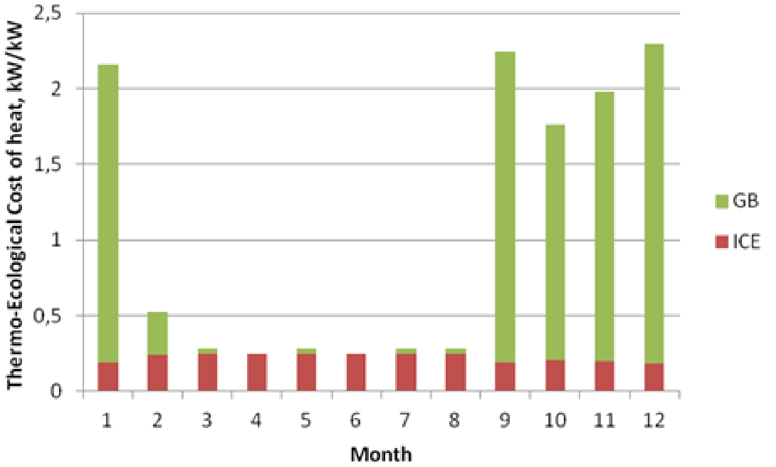


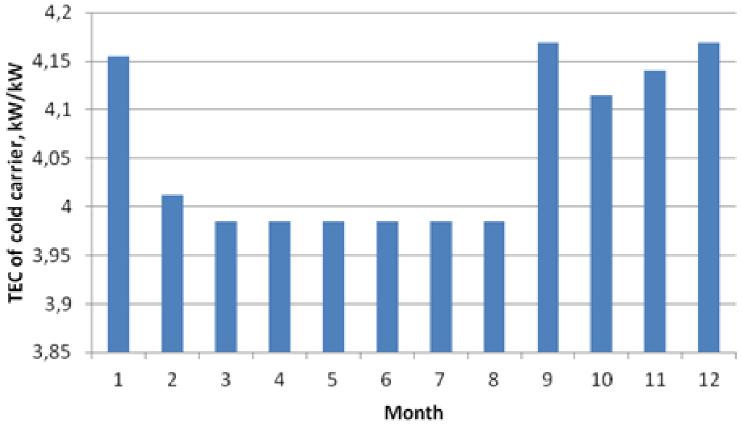


TEC examples (14)

Thermo-ecological assessment of CCHP plant supported with renewable energy





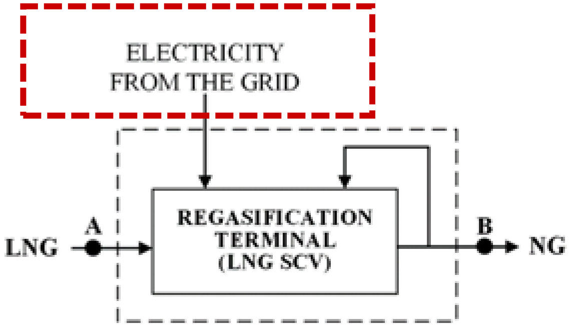


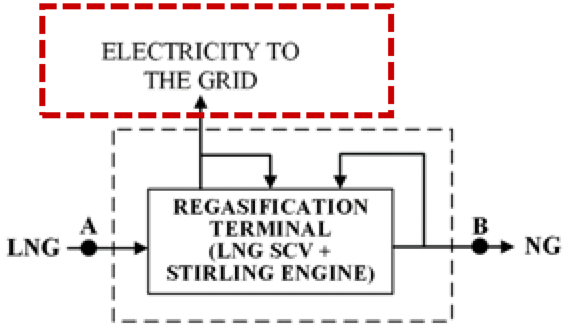
Both for the case of electricity and heat **it is possible to obtain the product TEC below unity**, which means that the exergy of (non-renewable) resources used to generate the product is less than the exergy value of that product. Due to use of non-renewable resources and due to the effects of pollutants and life cycle issues, it was not possible to achieve TEC = 0 for the final product, which would be a desired situation.

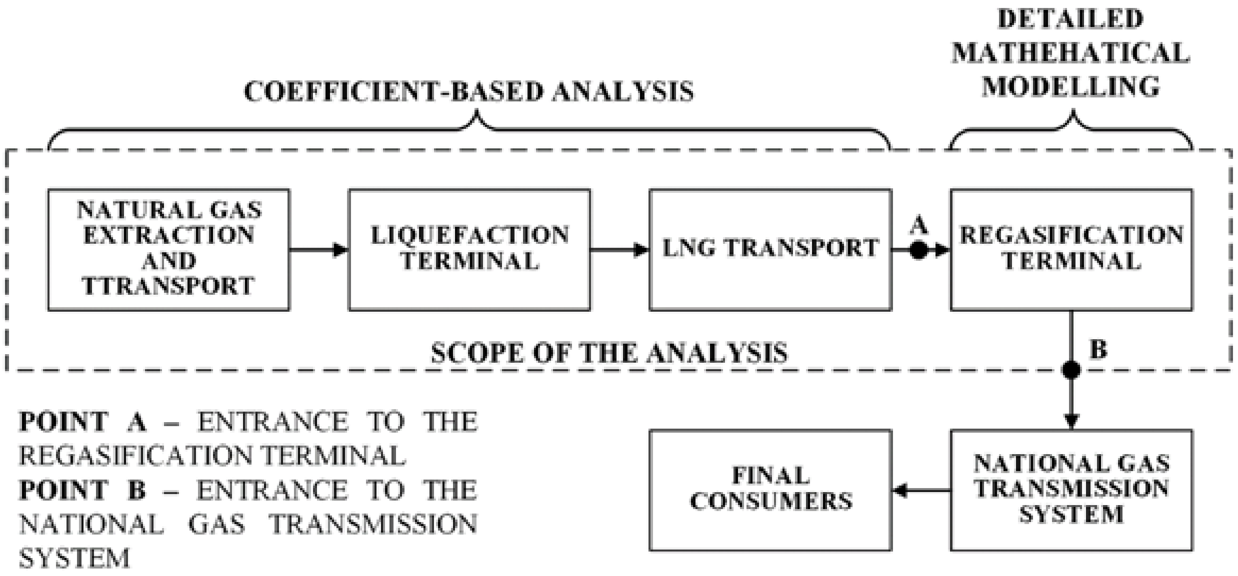
TEC examples (15)

Thermo-ecological analysis of power plant based on Stirling engine fed with cryogenic exergy of Liquid Natural Gas (LNG)

Motivation: The thermo-ecological cost analysis of cold power plant with Stirling engine fed with cryogenic exergy of Liquid Natural Gas.

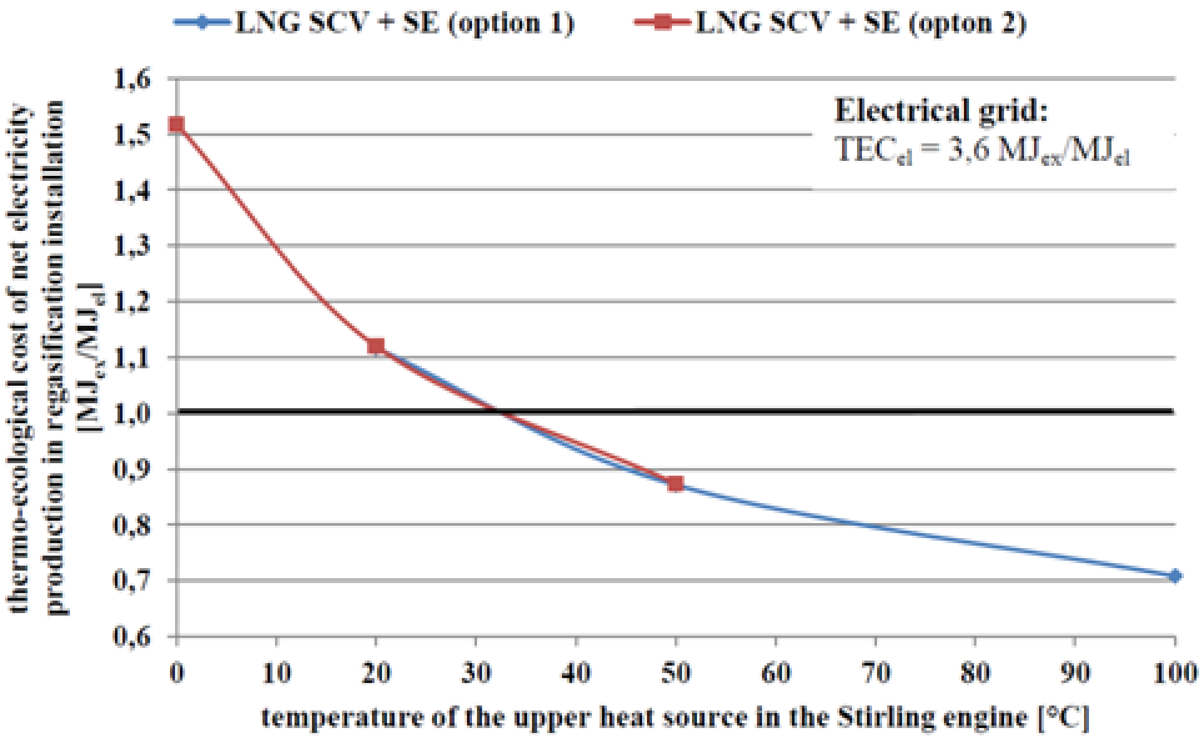


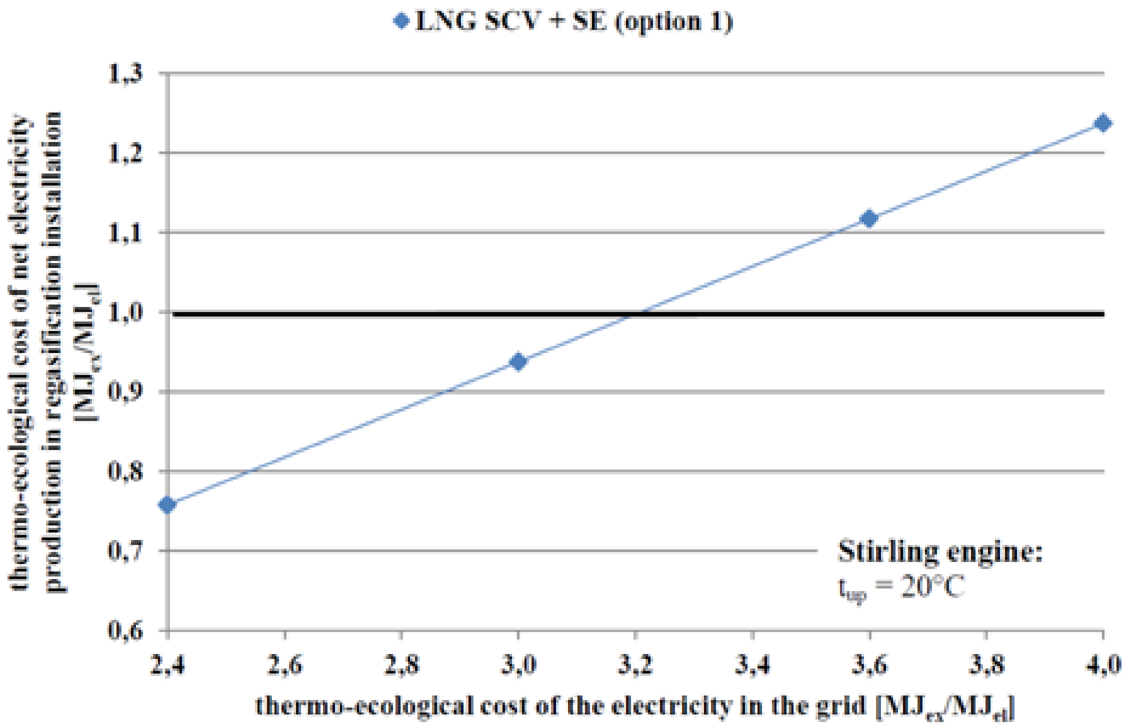




TEC examples (16)

Thermo-ecological analysis of power plant based on Stirling engine fed with cryogenic exergy of Liquid Natural Gas (LNG)

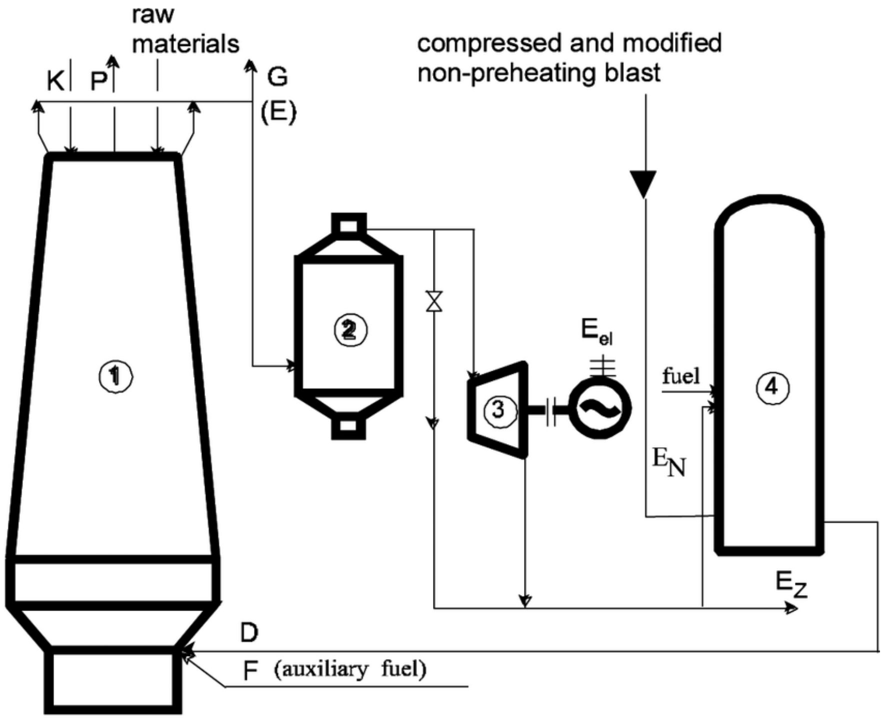




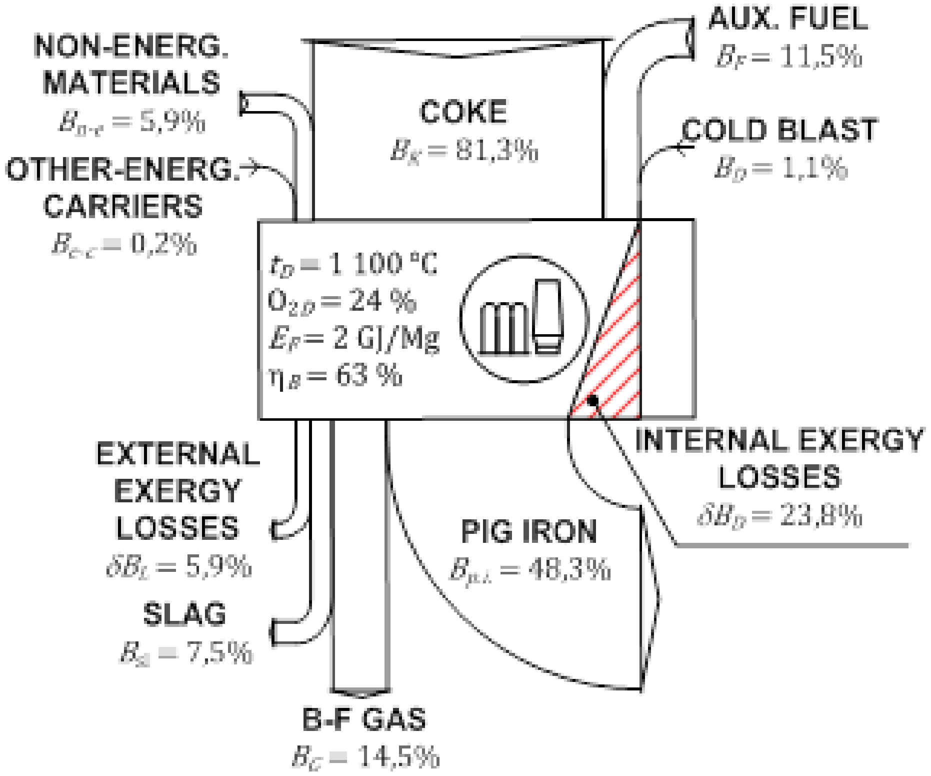
TEC examples (17)

Exergo-Ecological Assessment of Auxiliary Fuel Injection into Blast-Furnace

Motivation: Metallurgy represents a complex technological chain supplied with different kinds of primary resources.



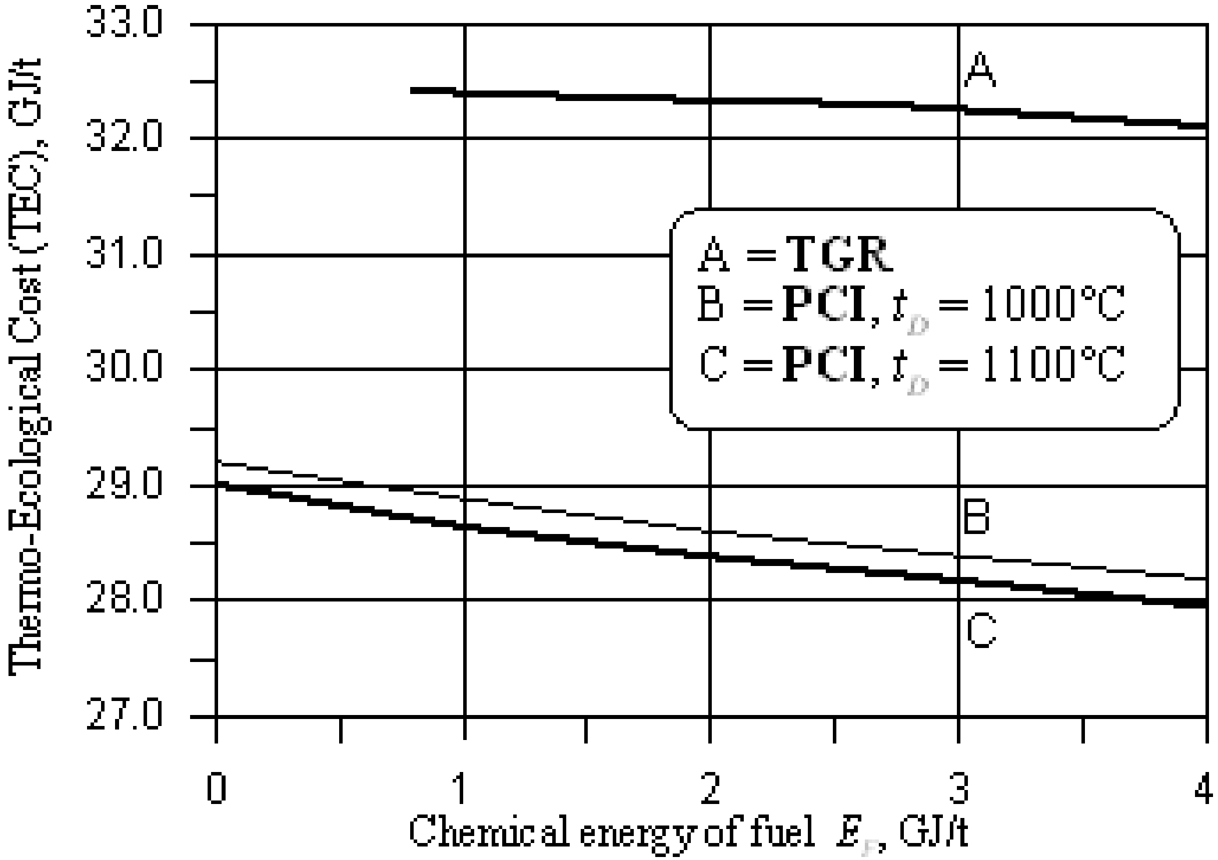
1 - BLAST FURNACE, 2 - GAS CLEANING PLANT,
3 - RECOVERY TURBINE OF TOP GAS,
4 - COWPER STOVE



TEC examples (18)

Exergo-Ecological Assessment of Auxiliary Fuel Injection into Blast-Furnace

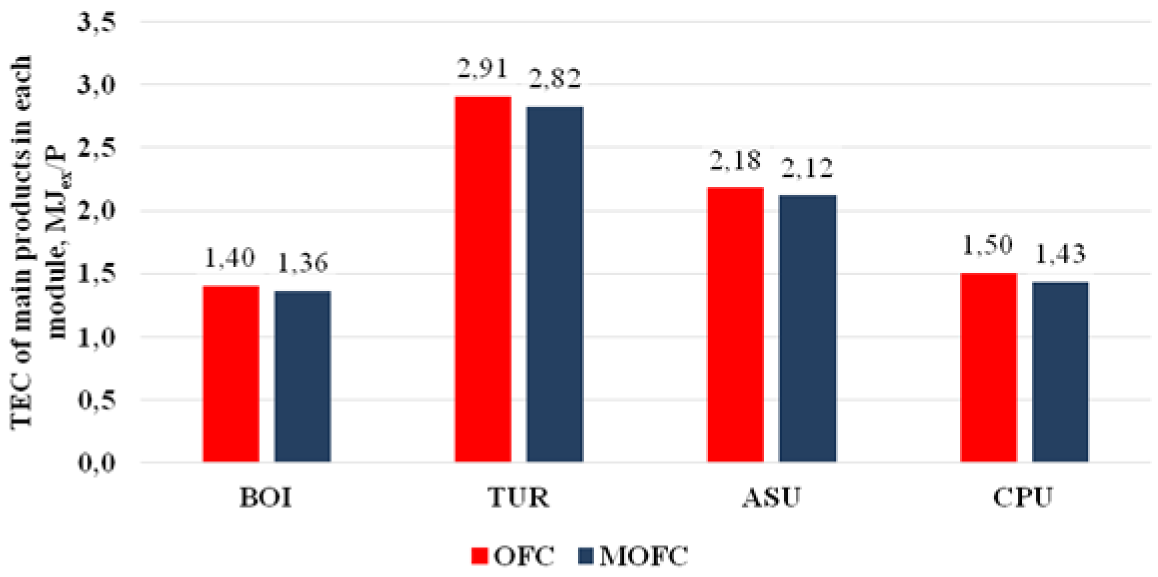
A. **top-gas recirculation (TGR) connected with CO_2 removal**,
B. pulverized coal injection (PCI) by blast temperature t_D = 1000°C,
C. pulverized coal injection (PCI) by blast temperature t_D = 1100°C.

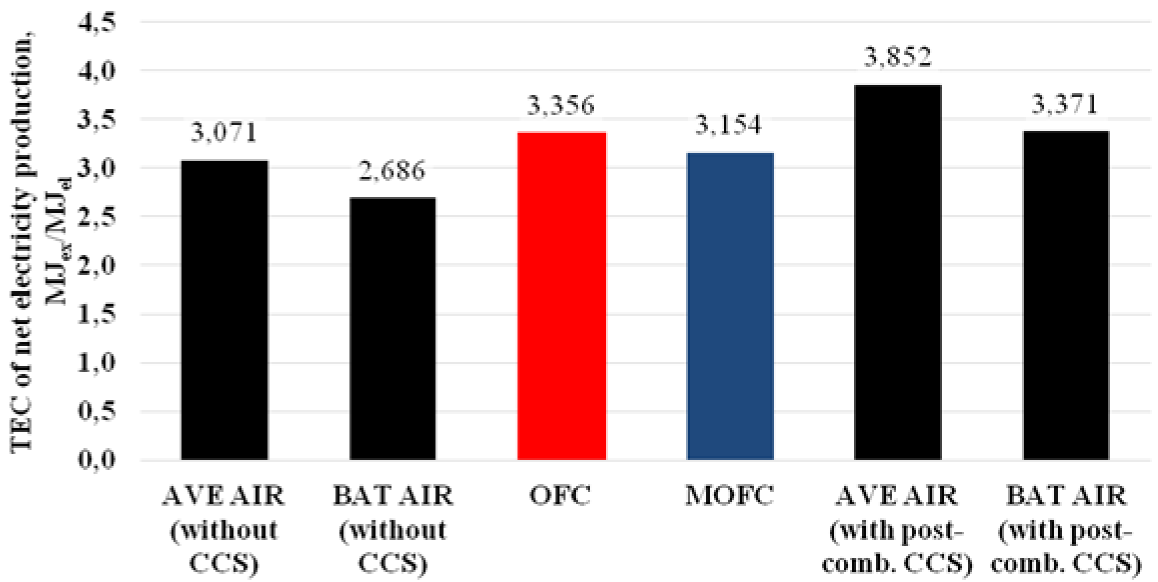


TEC examples (19)

Thermo-ecological evaluation of mild oxyfuel combustion power plant

Motivation: The Thermo-Ecological Cost (TEC) assessment of a new boiler design for a fossil fuel-based power plant with CO_2 capture, utilisation and storage (CCUS).

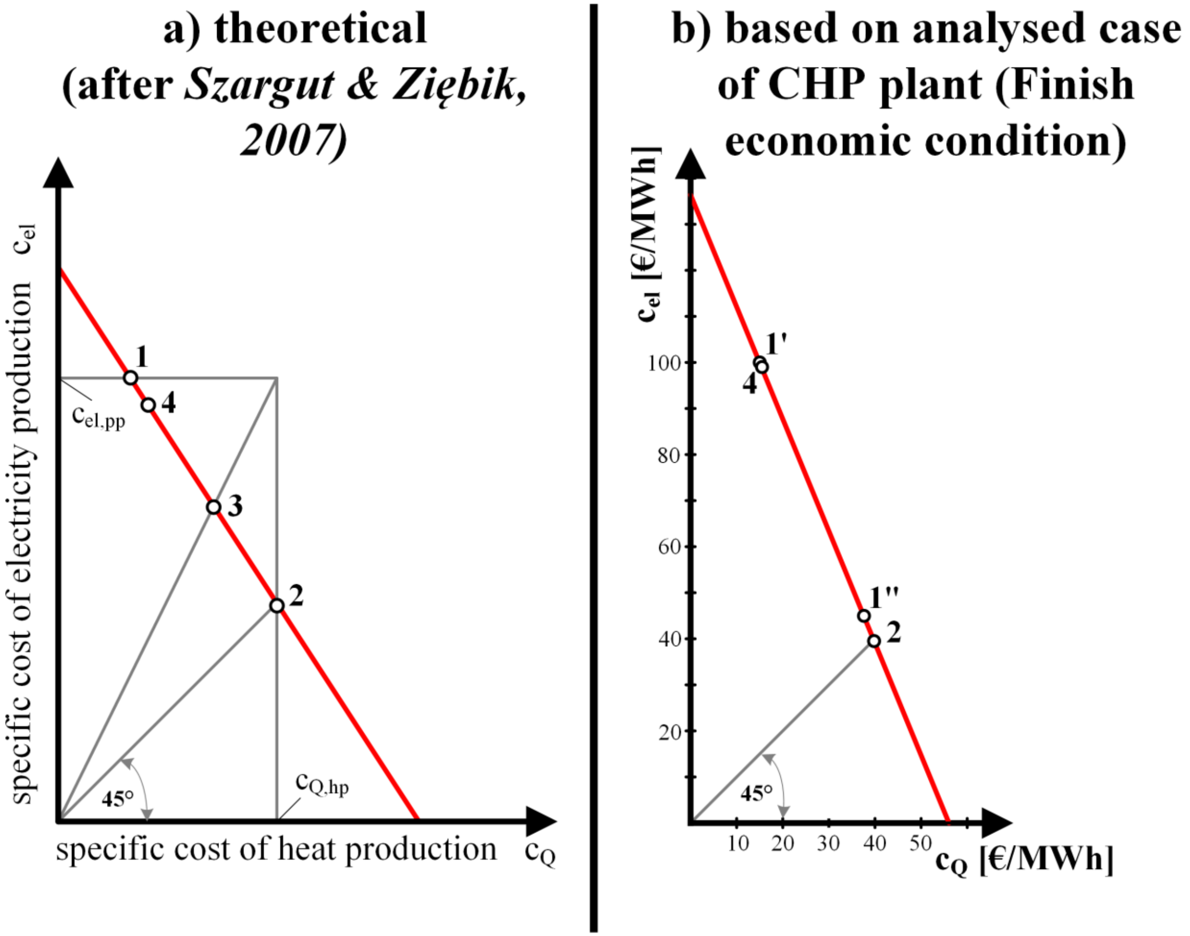




TEC examples (20)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

Motivation: The thermo-ecological cost allocation in cogeneration and polygeneration processes.

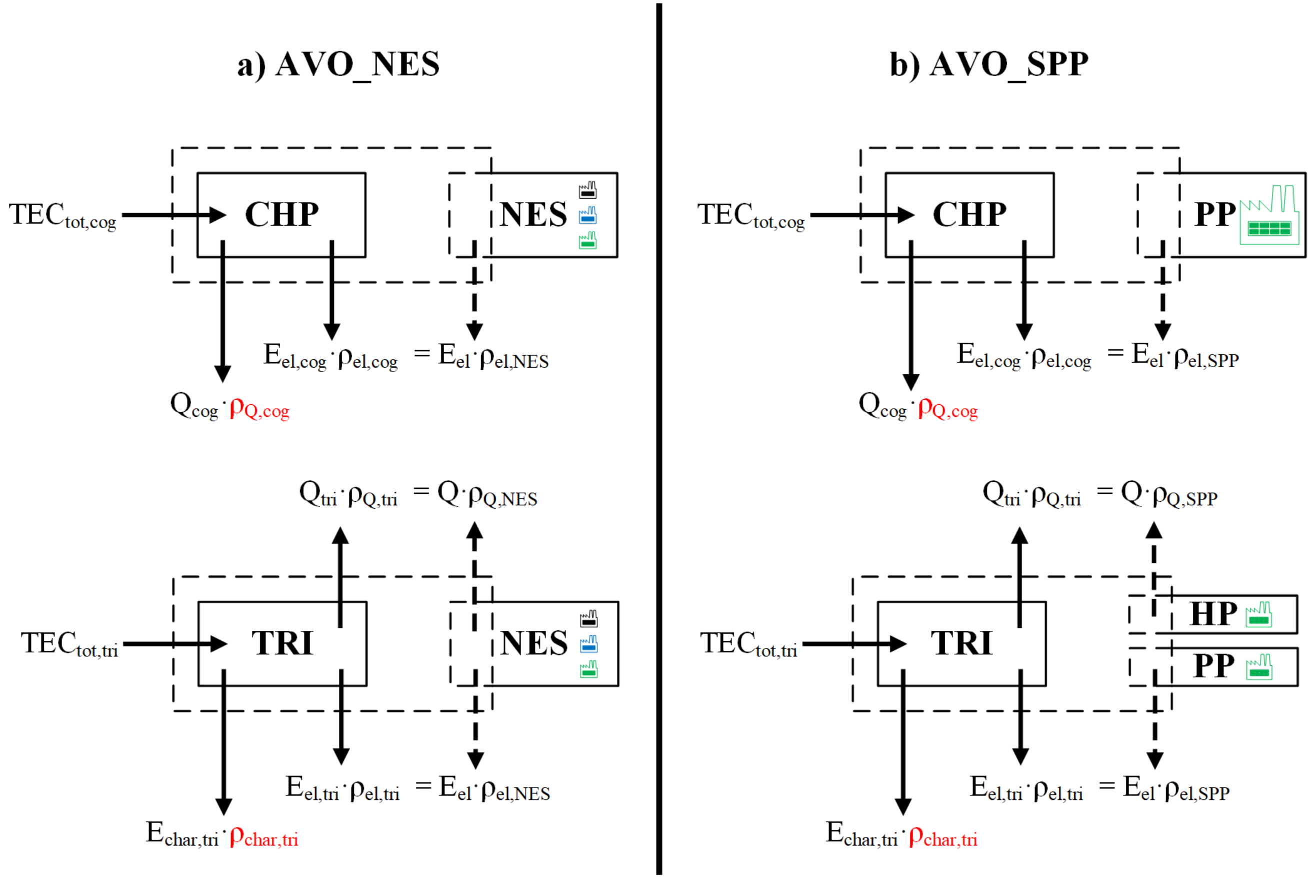


Economic cost allocation for CHP plant; 1 - avoided production; 2 - physical; 3 - compromise; 4 - exergetic; 1' - avoided production with c_{el} = 100 EUR/MWh; 1" - avoided production with c_{el} = 44 EUR/MWh

TEC examples (21)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

Motivation: The thermo-ecological cost allocation in cogeneration and polygeneration processes.

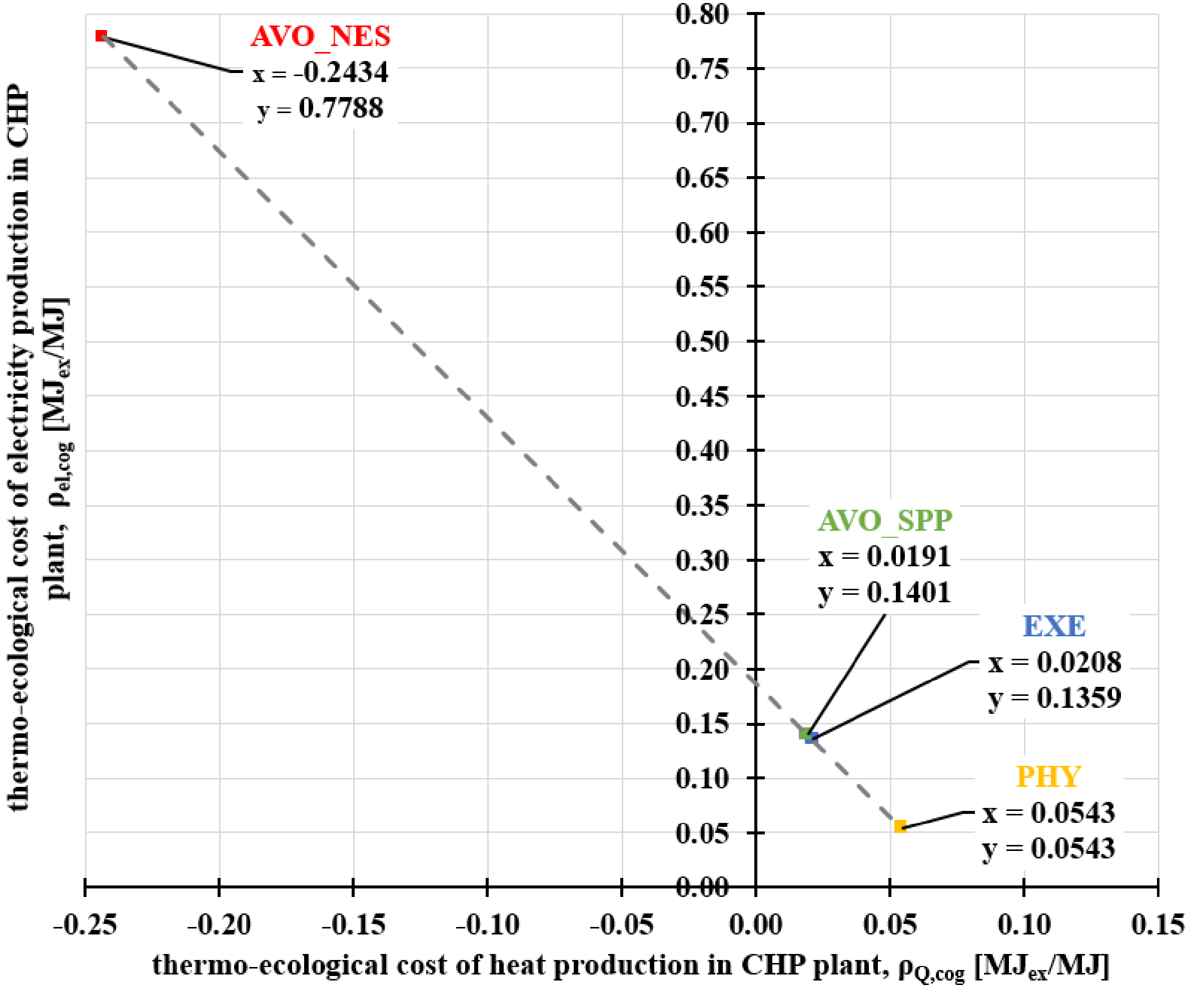


Avoided allocation methods (marked red are the values that can be calculated in given method)

TEC examples (22)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

Motivation: The thermo-ecological cost allocation in cogeneration and polygeneration processes.

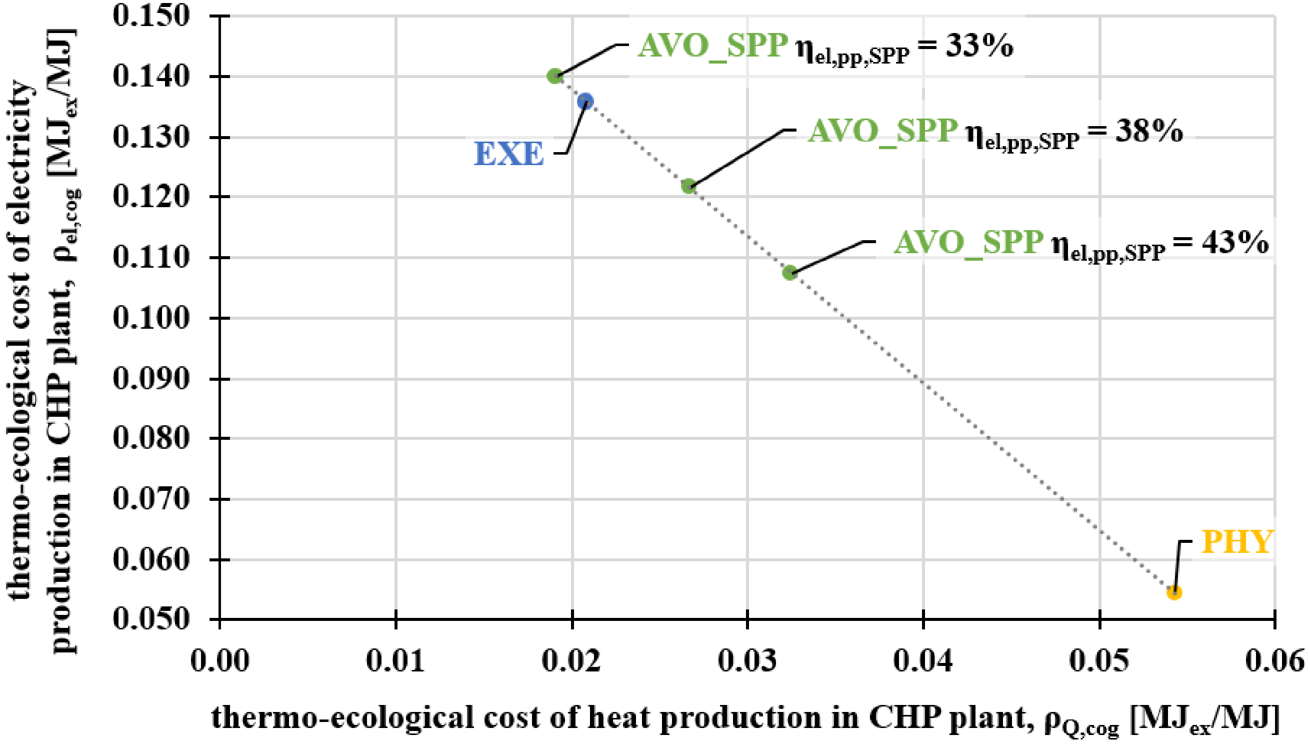


Results of TEC allocation in cogeneration technology (country: Finland)

TEC examples (23)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

<u>Motivation</u>: The thermo-ecological cost allocation in cogeneration and polygeneration processes.

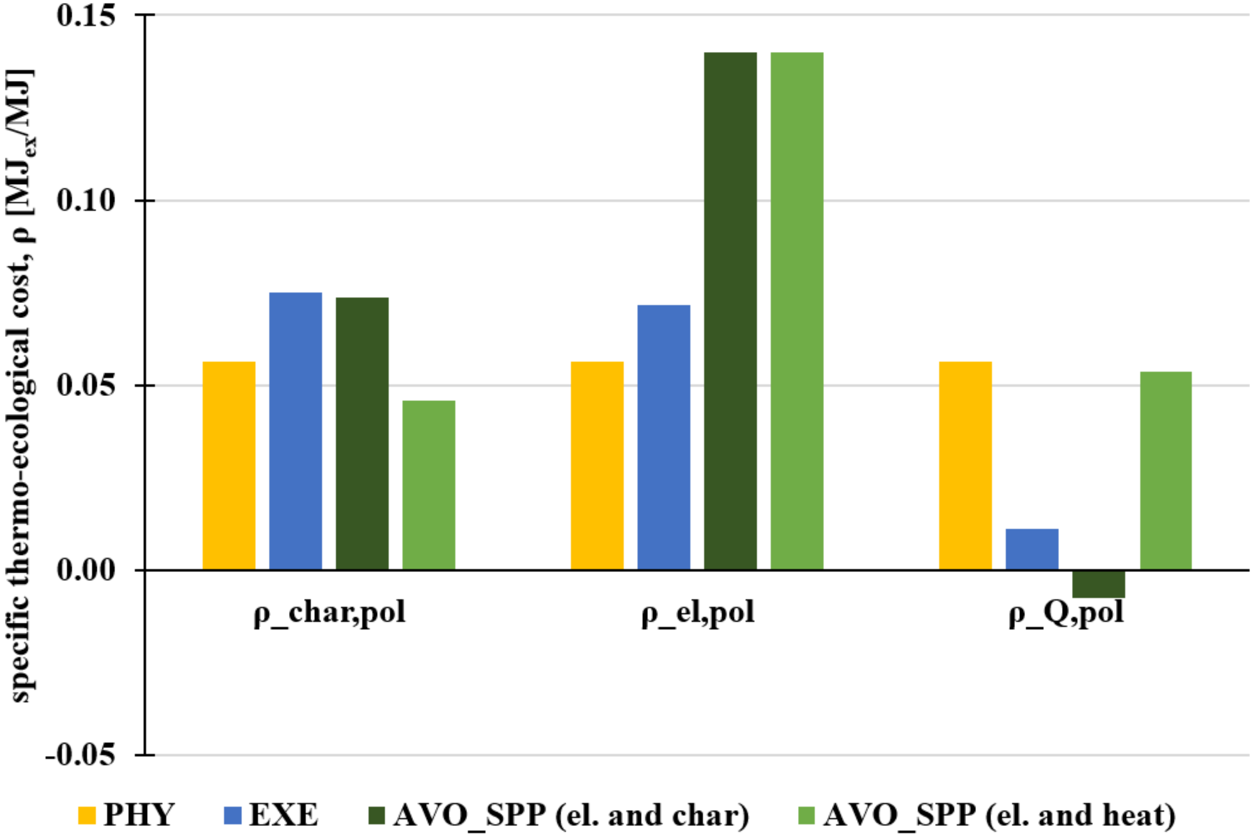


Results of sensitivity analysis concerning TEC allocation in cogeneration technology (country: Finland)

TEC examples (24)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

Motivation: The thermo-ecological cost allocation in cogeneration and polygeneration processes.

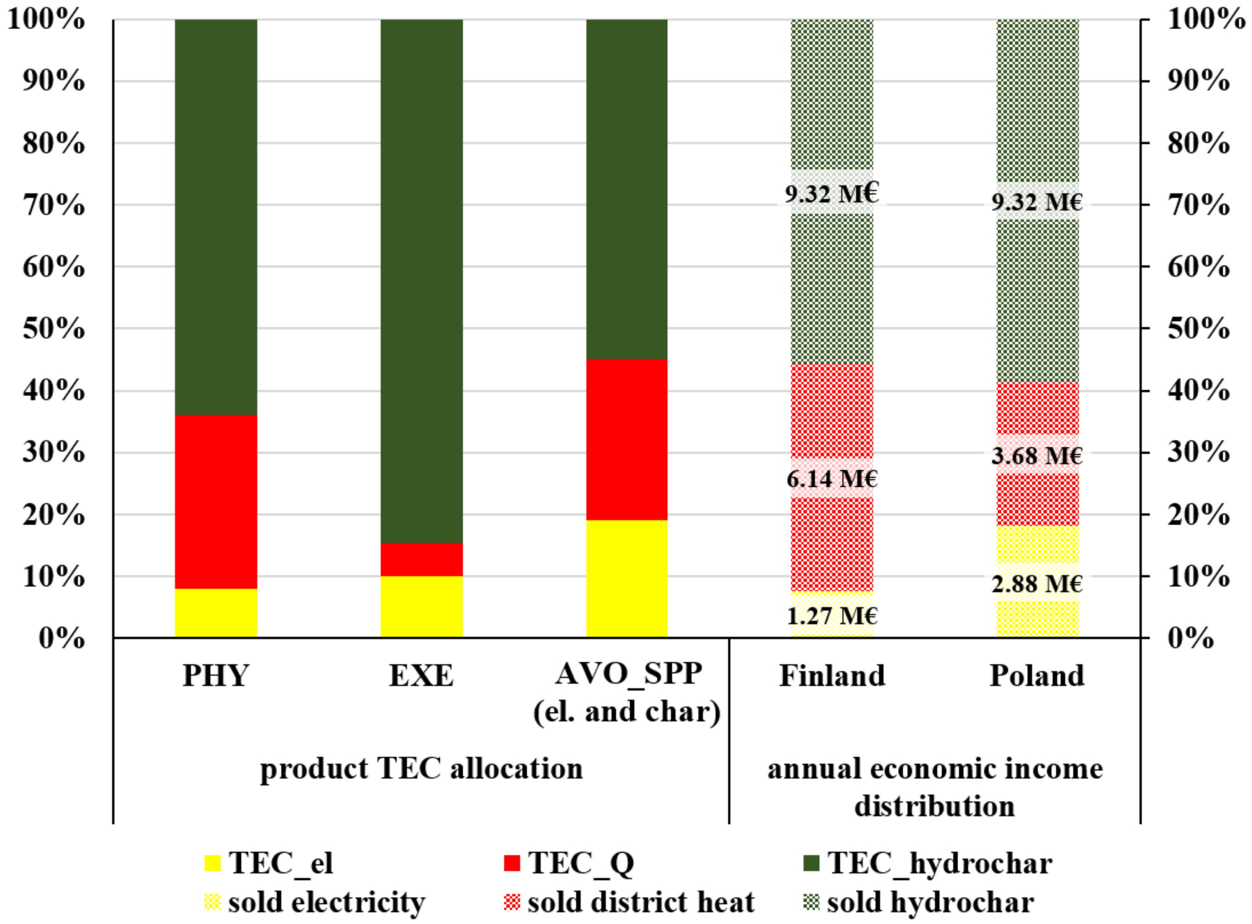


Results of the specific TEC of the products in polygeneration technology (country: Finland, technology: torrefaction, case: TOR_int)

TEC examples (25)

Thermo-ecological cost analysis of cogeneration and polygeneration energy systems - case study for thermal conversion of biomass

Motivation: The thermo-ecological cost allocation in cogeneration and polygeneration processes.



Results concerning share of TEC allocation in polygeneration technology (technology: HTC, case: HTC_int) and annual economic income

Pro-Ecological Tax (1)

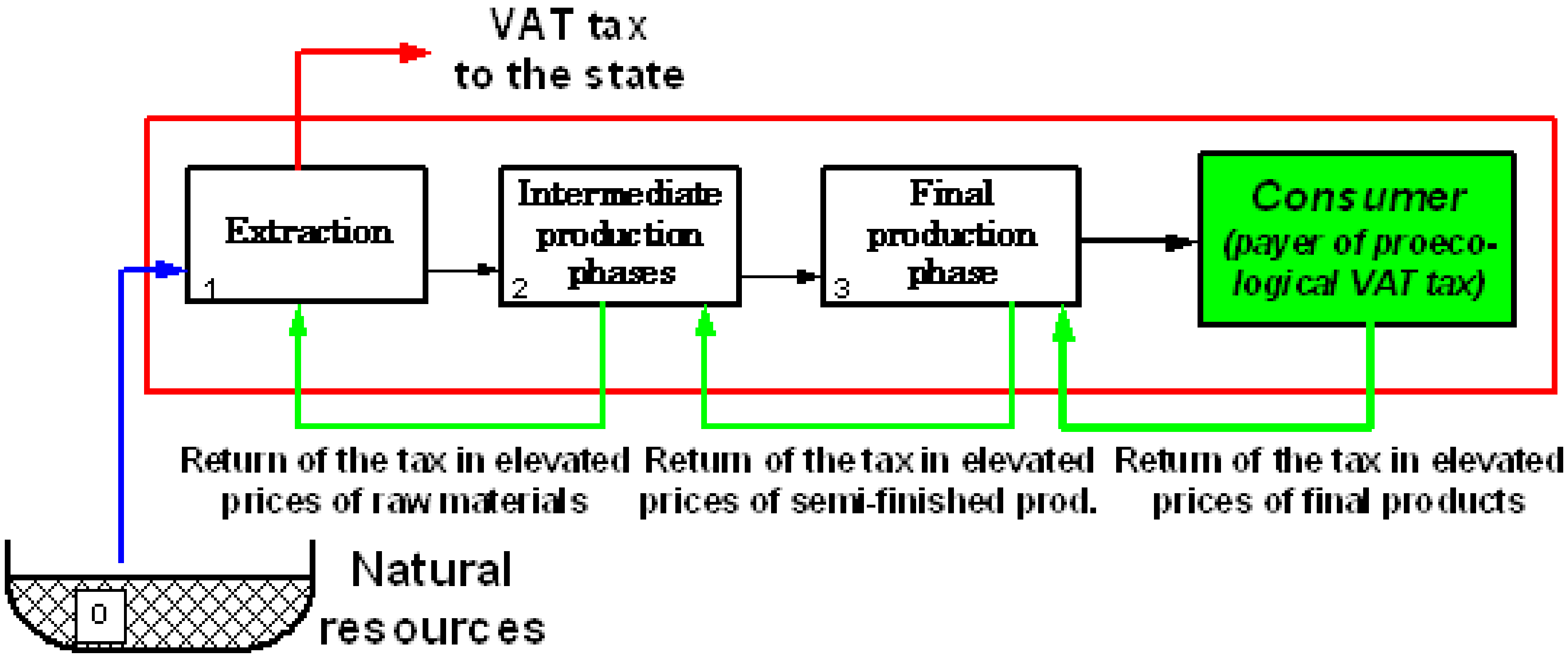
The concept of a **pro-ecological tax** or support mechanism was proposed by Professor Jan Szargut.

In the face of growing threat of exhaustion of non-renewable natural resources, the pro-ecological tax should take into account the influence of fabrication of consumption goods on the depletion of natural resources. It is proportional to the cumulative consumption of non-renewable natural exergy burdening the considered product expressed by TEC. **It could replace the existing value-added tax VAT.**

A principle which determines the coefficient of proportionality between the TEC and the value of the tax is that the income of the state after introducing the new tax **should remain without any changes.**

Pro-Ecological Tax (2)

The tax is eventually paid by the consumers of the final products in the form of an elevated price of goods and services.



Pro-Ecological Tax (3)

Concept of the exergy tax or subsidy depending on TEC index.

Thermo-Ecological Cost TEC_i MJ/MJ	Pro-ecological Tax – TAX, or Certificate - c_i € / MJ
$TEC_i > 1$	$TAX_i > 0$ (TAX)
$TEC_i = 1$	none
$TEC_i < 1$	$c_i > 0$ (subsidy)

Pro-ecological tax for non-renewable power technologies.

Technology i	p_i, €/MWh	TAX, %	Price with TAX, €/MWh
Hard coal	14.74	29.5	64.74
Lignite	10.27	20.6	60.27
Natural gas	3.50	7.0	53.50

Pro-Ecological Tax (4)

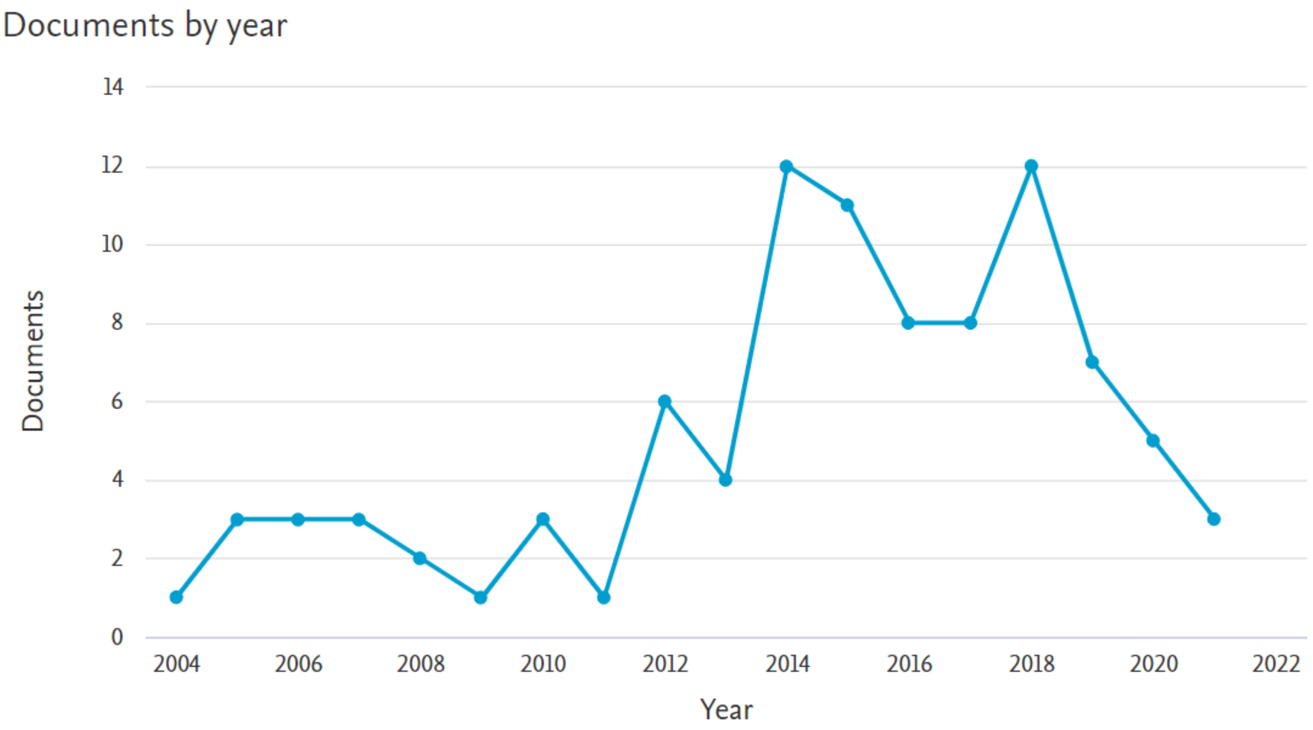
Pro-ecological support for renewable power generation

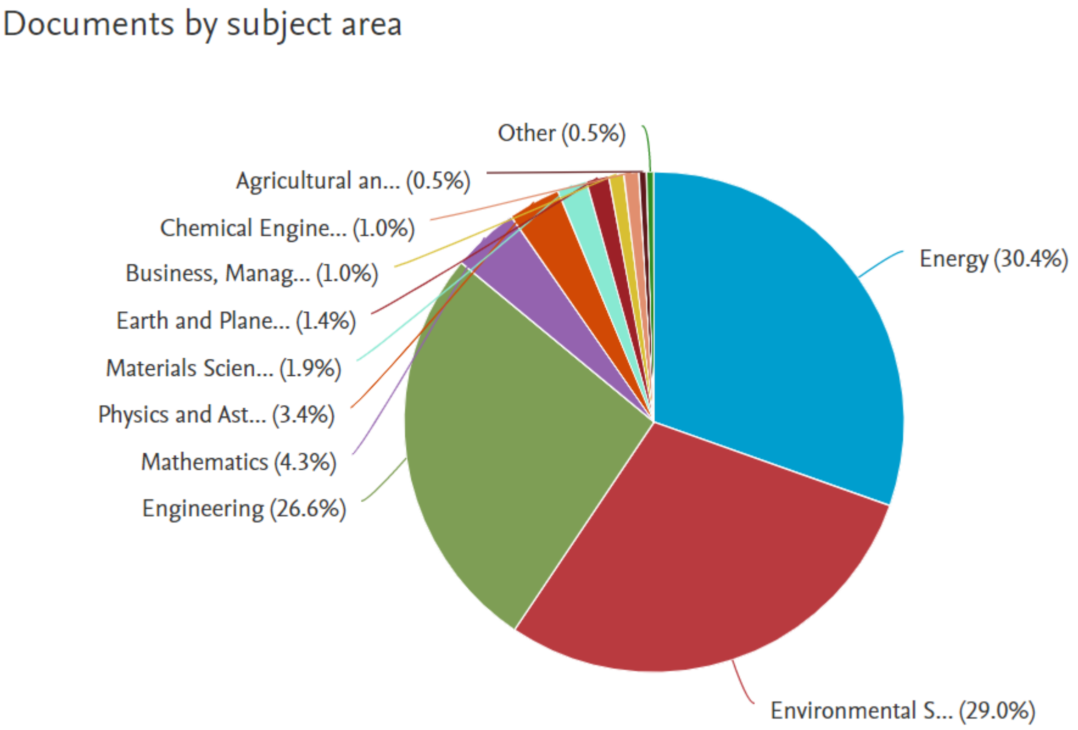
Technology	Share in national energy system,%	Exergy support		Administrative support	
		TEC, MJ/MJ	Certificate c_i, €/MWh	Coefficient	Certificate c_i, €/MWh
RES PV	2.00	0.26	**57.05**	2.85	**192.37**
RES Biogas	8.50	0.17	**64.00**	1.40	**94.50**
RES Hydro	2.40	0.01	**76.33**	1.90	**128.25**
RES Wind	11.10	0.09	**70.16**	0.90	**60.75**

The tax, which is proportional to the influence on the depletion of non-renewable resources, should be paid by technologies characterized by TEC higher than 1. The total income from this TAX should be distributed between technologies characterized by TEC lower than 1, such as renewable energy sources.

Summary (1)

Thermo-ecological cost **in literature** (Scopus) – 93 documents found





Summary (2)

Challenges for further development:

- TEC is facing the same challenges as any other LCIA method – allocation methods and available data (LCI).
- Mainly applied by research team at Silesian University of Technology (Gliwice, Poland) – 80% of the papers affiliated to SUT – needs to be recognised internationally.
- Over 200 processes and products assessed by means of TEC (mainly for Poland) – this is not enough!
- TEC for compensation of losses in environment - thermo-ecological evaluation of waste products and harmful emissions is very time and resource consuming.
- **TEC vs climate change and CO_2 emission** – it needs to be analysed in details (in progress).
- TEC development in terms of methods (in progress) and products/processes outside the energy industry.

Discussion

Thank you for you attention.