COMPLEX ANALYSIS OF RECUPERATION OF ENERGY POTENTIAL OF SECONDARY ENERGY RESOURCES (SER) IN A DEFINED CONTOUR

Roxana PĂTRAŞCU[1], Eduard MINCIUC[2]

În articol autorii au prezentat o metodologie pentru utilizarea unei analize complexe (care include aspecte energetice, de mediu şi economice) pentru recuperarea resurselor energetice secundare (RES). Metodologia include principalii paşi pentru inventarierea RES şi definirea criteriilor de eficienţă (energetică, de mediu şi economice) pentru recuperarea RES. Autorii au folosit metodologia propusă pentru analiza complexă a unui studiu de caz. Rezultatele obţinute conduc la concluzia că recuperarea RES poate fi o soluţie ideală pentru creşterea eficienţei energetice, iar internalizarea efectelor de mediu poate conduce la rezultate mai bune.

In the paper the authors present a methodology for using a complex analysis (including energy, environmental and economic aspects) of recovery of secondary energy recourses (SER). The methodology includes the main steps for the inventory of SER and definition of efficiency criteria (energy, environmental and economic criteria) for SER recovery. The authors have used the proposed complex analysis for a case study. The results show that SER recovery can be an ideal solution for increasing energy efficiency, and that internalisation of environmental effects can lead to better results.

Keywords: energy efficiency, secondary energy resources, energy recuperation

1. Introduction

The strategy approved by the Council of Europe in 2010 “Europe 2020 for an intelligent, sustainable growth” specifies a special objective that aims at increasing the energy efficiency with 20 %, [1].

Romania, as a member state of EU, has as a priority to promote the increase of energy efficiency through rational use of energy, by reducing at the same time the environmental impact through decreasing the use of the primary energy resources.

[1] Reader, Depart. of Energy Production and Use, University POLITEHNICA of Bucharest, Romania, e-mail: op3003@yahoo.com
[2] Lecturer, Depart. of Energy Production and Use, University POLITEHNICA of Bucharest, Romania, e-mail: eduard.minciuc@energ.pub.ro

The most used solutions for increasing energy efficiency in industrial companies aim at recovering the energy from the secondary energy resources (SER), [2 and 3].

All technological processes are characterised by inevitable energy losses, which can be considered as secondary energy resources. The most of these “energy losses flows” are characterised by energy potential that can be used and represent secondary energy resources (SER).

The analysis of the complex efficiency (energy, environmental and economic) of the recovery of secondary energy resources within a industrial technological process is performed for a specific contour at a specific moment, which is characterised by specific technical, economic and financial conditions. For these conditions only a part of the SER potential can be recovered in an efficient way; this part represents the re-useable energy resources (RER). Due to this fact, RER which are very much dependent on the technologies used for recovery and on the reference level of the costs of different energy flows and materials used have a dynamic character over the time.

The great variety of technological processes lead to a large number of SER, depending on the energy flow used, nature of the energy flows and the recovery direction that has been used.

2. The main steps for inventory of SER

The inventory of SER is a preliminary phase for establishing the directions and solutions for possible energy recovery. In order to have a correct image of the potential of SER within a contour there is a need to follow these steps:

- Establish a reference contour for SER (a device, equipment, technological line, company, industrial platform, etc.).
- Perform an energy analysis of the processes within the analysed contour, based on the energy and exergy balances, identifying energy losses compared to the “useful effect”.
- Apply solutions for increasing the energy efficiency of the analysed contour (without costs or with minimal costs) for reducing energy losses within the technical-economic profitability, in order to avoid recovery of those energy losses that not lead to positive financial effect.
- Quantitative and qualitative analysis of the new losses for each energy flow compared to the reference conditions of the environment, concluding to potential thermodynamic limits.
- Establish technical solutions for SER recovery for each energy flow, taking into consideration the quantitative and qualitative aspects of the recovered energy flow and possible utilisation solutions.

- Establish the types of the equipment that should be used for SER recovery together with their technical characteristics, excluding possible technical limitations.
- Perform a complex analysis quantifying the energy, environmental and economic efficiency (based on criteria) of SER recovery. Based on this analysis establish the direction and optimal degree of SER recovery and its energy, environmental and economic effects, [4].

3. Efficiency criteria for SER recovery

3.1. Energy efficiency criteria for SER recovery

There can be defined the following energy efficiency criteria for evaluation of SER recovery:

- Fuel equivalent of saved energy (brut and net value of fuel savings, in absolute and relative values).
- Energy recovery degree.

Table 1 shows the equations for the energy efficiency criteria.

Table 1

Energy efficiency criteria

Energy efficiency criterion	Equation
Fuel savings	$\Delta B=\Delta W/Hi$[kgfuel/τ]
Absolute brut value	$\Delta Bb = \Delta Wb/Hi$ [kgfuel/τ]
Absolute net value	$\Delta Bn = \Delta Wnet/Hi$ [kgfuel/τ]
Relative brut value	$\Delta bb= \Delta Bb / Bi$
Relative net value	$\Delta bn= \Delta Bn / Bi$
Energy recovery degree	$\delta=wgar / wga$

The terms in the table above have the following description:

ΔW represents the energy savings through implementation of the recovery solution, absolute value, kJ/τ.

ΔB_b represents the equivalent in fuel of brut energy savings through implementation of the recovery solution, absolute value, kJ/τ.

ΔB_n represents the equivalent in fuel of net energy savings (brut energy savings minus the energy consumption of the recovery equipment) through implementation of the recovery solution, absolute value, kJ/τ.

B_i represents the initial fuel consumption of the equipment (without recovery), kJ/τ.

Hi represents the lower heating value of the fuel savings, kJ.kg, or kJ/kg c. f. of conventional fuel.

τ represents the reference time for the calculation (duration of the applied recovery solution, s.
Wga represents the energy content of SER, kJ/τ.
Wgar represents the energy recovered from SER, kJ/τ.

3.2. Environmental criteria for SER recovery

Establishing and calculation of the environmental impact criteria for SER recovery solution allow quantification of the environmental impact of the proposed solutions, which is very important for energy efficiency measures implementation.

Each type of the environmental impact can have different criteria that can be used for evaluation of SER recovery solutions. The calculation of the environmental impact criteria can be performed taking into account quantities of pollutant emissions during the analysed period within the analysed industrial contour.

These criteria are established taking into account the effects (direct and indirect) of heat recovery from the flue gasses.

Thus, the evacuation of flue gasses with high thermal potential into atmosphere leads to evacuation of a heat quantity into the environment changing the biologic equilibrium, and, at the same time, leading to evacuation into atmosphere of the chemical pollutants: SOx, NOx, dust, etc.

The norms for environmental pollution, valid with EU, set values for air quality and fiscal taxes for atmosphere pollution, [5, 6 and 7].

Economic internalisation of the environmental effect of SER recovery can be quantified through eco-taxes that are paid in case of exceeding the permitted limits of the pollutant emissions, set by legislation regarding environmental protection.

Examples of environmental impact criteria that can be used for environmental evaluation of SER recovery.

A. Eutrophisation – has as effect increasing the consumption of oxygen due to high concentration of the nitrogen and phosphate products. Contribution to the eutrophisation phenomena of a given substance “i” is represented by the eutrophisation potential NP, kg/$PO4^{3-}$.

$$NP=\sum m_i * NP \quad [kg_{PO43^-/year}] \qquad (1)$$

Where: NP represents the eutrophisation potential of a given substance “i” and m_i represents the quantity of substance “i”, [8 and 9].

B. Acidiphication – represents the change of the equilibrium of the atmosphere due to gas emissions with acid from the technological processes that are analysed. The most used criterion is the equivalent acidity (compared with SO_2).

$$\Delta P = \sum m_i * AP_i \ [kg_{SO2}/year] \quad (2)$$

Where: ΔP represents the potential of acidity of a given substance "i" and m_i represents the quantity of substance "i", [8 and 9].

C. Photo-oxidant pollution – can appear due to photochemical reaction of nitrogen components and volatile organic components at the base of troposphere, under influence of ultraviolet radiation. One of the most important photo-oxidant is ozone. The equation for calculation of formation potential of the photochemical ozone is presented bellow.

$$POCP = \sum m(POCP * m_i) \ [kg_{C2H4}/year] \quad (3)$$

Where: $POCP_i$ represent the criteria for creation of the photochemical ozone for a given substance "i" and m_i represents the quantity of substance "i", [8 and 9].

D. Contribution to the depletion of reserves of natural raw materials – characterises the degree of endangered raw material that can disappear due to its consumption. It allows estimation of contribution of the production sector to the depletion of reserves of natural raw materials as a dependence of how much raw materials are used.

$$ERN = \sum (m_i/a) \ [m^3_N] \quad (4)$$

Where: "a" represents the period of abundance of the specific raw material used, [8 and 9].

3.3. Economic criteria for SER recovery

Economic efficiency of SER recovery can be established by taking into account energy savings $C_{\Delta B}$ (in fuel equivalent) that have been achieved through an investment action and with yearly expenses for the energy recovery equipment.

For SER recovery expenses are calculated directly for the SER recovery equipment, and indirect by occasional expenses (auxiliary equipment) and additional energy consumption of the SER recovery equipment.

The economic efficiency of increasing energy efficiency within an industrial contour comes from reducing the production expenses, which can lead to reducing the costs of the final products.

The economic efficiency of SER recovery is established compared to situation without SER recovery. When analysing several solutions, the optimal one is established through comparative economic analysis of each solution with reference one (without SER recovery).

The SER recovery solution, which leads to the maximum economic effect, based on an economic criterion, is considered to be the optimal one.

The most used economic criterion is the "Payback period". It can be calculated as presented in the equation bellow.

$$TR = \Delta I / \Delta C \quad \text{(years)} \tag{5}$$

Where: ΔI represents the investment surplus for the SER recovery solution and ΔC represents the financial savings.

For the case when eco-taxes are used the payback period is calculated as shown in equation bellow.

$$TR^{*} = \Delta I / \Delta C + \Delta Ec \tag{6}$$

Where: ΔEc represents the expenses savings due to eco-taxes.

4. Case study - Complex analysis of heat recovery from the flue gasses

4.1. Presentation of the analysed solution

- The analysed industrial contour: furnace for thermal treatment.
- The energy audit has revealed the following: the energy efficiency of the furnace that uses natural gas is very low, having great energy losses.
- The inventory of the secondary energy resources has revealed the following:
  - A high energy potential of the flue gasses of the furnace.
  - Taking into account that the flue gasses temperature is very high due to the fact that the temperature inside the furnace is about 1000 °C, the main energy losses occur with flue gasses.

Taking into consideration all the aspects presented above there has been proposed a SER recovery solution. This solution consists in internal heat recovery from flue gasses for pre-heating the combustion air. The furnace operation time has been considered as being 7,200 h/year.

Within the case study there will be analysed the complex efficiency of the proposed solution: energy efficiency analysis, environmental and economic analyses of installation of the heat recovery equipment for pre-heating of combustion air.

For the complex analysis there have been considered the following data:

- Thermo-physical characteristics of SER.
- SER parameters.
- Chemical composition of SER.
- Atmospheric emissions due to presence of SER.
- Economic data (specific costs, etc.).

Evaluation of the energy, environmental and economic efficiencies of heat recovery from flue gasses for pre-heating the combustion air will be performed using energy, environmental and economic criteria.

4.2. Energy efficiency calculus for implementation of heat recovery solution from flue gasses for pre-heating combustion air

Table 2 shows the main initial data used for calculation of the heat recovery exchanger for pre-heating of combustion air.

Table 2

Main initial data for the industrial furnace

No.	Criterion	Notation	Measure	Value
1	Lower calorific value	Hi	kJ/m3N	36,000
2	Fuel consumption before recovery	B1	m3N/s	0.349
3	Air temperature before recovery	tae	°C	20
4	Air temperature after recovery	tai	°C	500
5	Flue gasses temperature at inlet pre-heater	tg	°C	1,000
6	Flue gasses temperature at outlet pre-heater	tgev	°C	380
7	Excess air coefficient before recovery	λ1	-	1
8	Excess air coefficient after recovery	λ2	-	1.2
9	Initial temperature of the fuel	tc	°C	20

The main analysis steps are the following:

- Calculus of the thermodynamic properties of the air, fuel and flue gasses.
- Combustion process calculus.
- Calculus of the heat flows for flue gasses, air and fuel (in and out the analysed contour).
- Energy balance for the analysed contour.
- Calculus of the energy efficiency criteria (fuel savings in absolute and relative values and energy recovery degree).

Table 3 presents the main steps of calculation and obtained results.

Table 3

Main steps of calculation and obtained results

No.	Criterion	Notation	Measure	Equation	Value
1	Theoretic volume of flue gasses	Vg0	m3n/ m3n	-	13.5
2	Theoretic volume of combustion air	va0	m3n/ m3n	-	12.5
3	Real volume of flue gasses before pre-heater	Vg1	m3n/ m3n	Vg1 = Vg0+(λ1-1) Va0	13.5
4	Real volume of air before pre-heater	Val	m3n/ m3n	Va1=λ1*Va0	12.5
5	Real volume of flue gasses after pre-heater	Vg2	m3n/ m3n	Vg2 = Vg0+(λ2-1) Va0	16
6	Real air volume after pre-heater	Va2	m3n/ m3n	Va2=λ2*Va0	15
7	Enthalpy of flue gasses after furnace	ig	kJ/m3N	ig=cpg*tg	2000.2
8	Enthalpy of flue gasses at evacuation in atmosphere	igev	kJ/m3N	igev=cgev*tgev	671.878
9	Enthalpy of combustion air (without recovery)	iae	kJ/m3N	iae=cpae*tae	25.952
10	Enthalpy of combustion air (with recovery)	iai	kJ/m3N	iai=cpai*tai	655
11	Fuel enthalpy	ib	kJ/m3N	ib=cpb*tb	44.24
12	Fuel consumption for solution with recovery	B2	m3N/s	B2=B1*rPA	0.2356
13	Flue gasses heat contain for solution without recovery	Qg1	kW	Qg1=B1* Vg1*ig	9423.94
14	Flue gasses heat contain for solution with recovery	Qg2	kW	Qg2=B2* Vg2*ig	7539.955
15	Heat introduced with air for solution without recovery	Qal	kW	Qa1=B1 *λ* va0iae	113.215
16	Heat introduced with air for solution with recovery	Qpa	kW	QpA= B2*Va2*iai	2314.77
17	Heat introduced with fuel for solution without recovery	Qc1	kW	Qc1=B1*(Hi+ib)	12579.449
18	Heat introduced	Qc2	kW	Qc2=B2(Hi+ib)	8492.023

No.	Criterion	Notation	Measure	Equation	Value
	with fuel for solution with recovery				
19	Brut fuel savings (absolute value)	ΔB'	m3N/s	ΔB'=B1*(1-rPA)	0.1134
20	Net fuel savings (absolute value)	ΔB	m3N/s	ΔB= ΔB'- ΔBsupl	0.1131
21	Net annual fuel savings (absolute value)	ΔBanual	m3N/an	ΔBanual= ΔB*τu	29315*104
22	Brut fuel savings (relative value)	Δb'	%	ΔB'/ B1	32.5
23	Net annual fuel savings (relative value)	Δb	%	ΔB/ B1	32.4
24	Energy recovery degree	δPA	-	δPA= QpA / Qg2	0.31

Note: :r_{PA}- has been calculated as a ratio between fuel consumption of furnace before and after implementation of the recovery solution.

$$r_{PA} = \frac{B_2}{B_1} = \frac{H_i + i_b - \lambda_1 * v_{a0}(i_g - i_{ae}) - i_g(v_{g0} - v_{a0})}{H_i + i_b - \lambda_2 * v_{a0}(i_g - i_{ai}) - i_g(v_{g0} - v_{a0})} =$$

$$r_{PA} = \frac{36000 + 44.24 - 1*12.5*(2000.2 - 25.952) - 2000.2*(13.5 - 12.5)}{36000 + 44.24 - 1.2*12.5*(2000.2 - 655) - 2000.2*(13.5 - 12.5)} = 0.675 \quad (7)$$

4.3. Environmental impact calculus for implementation of heat recovery solution from flue gasses for pre-heating combustion air

The calculation of environmental impact criteria is performed compared to the reference solution (without heat recovery).

The main steps of the environmental analysis are the following:

- Calculation of the flow of flue gasses (for both solutions with and without recovery).
- Calculation of annual quantities of atmosphere pollutants (for both solutions with and without recovery).
- Calculation of the environmental impact criteria (for both solutions with and without recovery).
- Calculation of reduction of environmental pollution due to implementation of the heat recovery solution.

➢ **Solution without heat recovery (the reference solution):**

D_{ga}=B_1*Vg=0.349*13.5=4.7115 [m^3_N/s] (8)

Table 4

Atmospheric emissions (reference solution)

Emission type	Specific value, [mg/m3N]	Annual value, t/year
SO2	0.7	85.48
NOx	305	18.88
CO	17	1.05
Dust	8	0.49

- ERN= 9046080/50=181 [m^3_N].
- Acidification: AP=Σ(m_i*AP_i), where: AP_{SO2}=l; AP_{NOx}=0.7 (9)

  AP=$(m*AP)_{S02}$ +$(m*AP)_{NOx}$ =85.48*1+18.88*0.7=98.69 [t_{SO2}/year] (10)
- Eutrophisation: NP= Σ (m_i*NP_i), where: NP_{NOx} =0.13 (11)

  NP=$(m*NP)_{NOx}$ =18.88*0.13 = 2.45 [t_{P043-}/year] (12)
- Dust emissions: Ipr= $\Sigma \frac{m_i}{C_j}$, where: Cj=0.07 (13)

  $$I_{PB} = \frac{0.49}{0.07} = 7[t_{dust} / year] \quad (14)$$
- Photooxidant emissions: POCP= Σ (POCP*m_i), unde:$POCP_{CO}$=0.036 (15)

  D_{ga} = B_2* V_g=0.235* 13.5=3.172 [m^3_N/s] (16)

➢ **Implementation of the heat recovery solution**

D_{ga} = B_2* V_g=0.235* 13.5=3,172 [m^3_N/s] (17)

Table 5

Atmospheric emissions (solution with heat recovery)

Emission type	Specific value, [mg/m3N]	Annual value, t/year
SO2	0.7	57.55
NOx	305	12.72
CO	17	0.8
Dust	8	0.33

- ERN= 122 [m^3_N] (18)

AP=$(m*AP)_{S02}$ +$(m*AP)_{NOx}$ =57.55*1+12.72*0.7=66.45 [t_{SO2}/ year] (19)

NP=(m*NP)NOx =12.72*0.13 = 1.65 [tP043-/year] (20)

$$\text{Ipb}=I_{pb}=\frac{0.33}{0.07}=4.71[t_{dust}/year] \quad (21)$$

POCP=(m*POCP)CO = 0.71*0.036 = 0.025 [tC2H4 /year] (22)

Table 6

Envirnomental impact criteria

Criterion	Measure	Annual reduction
ΔERN	[m3N]	59
ΔAP	[tSO2/ year]	32.24
ΔNP	[tP043-/year]	0.71
ΔPOCP	[tC2H4 /year]	0.33
Δ Ipb	tdust/year	0.013

4.4. Economic efficiency calculus for implementation of heat recovery solution from flue gasses for pre-heating combustion air

1. Investment value for the heat recovery solution

I_{PA} = 78253.15 [Euro] (23)

2. Difference of the annual expenses

$\Delta C_{PA}=C_{\Delta B}-C_{PA}$ [Euro/year] (24)

Where: $C_{\Delta B}$ - represents the savings due to fuel savings.
C_{PA} - represents the annual operation expenses for pre-heater.

- Annual expenses savings due to fuel savings

$C\Delta B = \Delta B_{anual} * p_c$ [Euro/year] (25)

Where: ΔB_{year} – annual fuel savings, m^3_N/year.
p_c – fuel price, Euro/MWh.

- Annual operating expenses

$C_{ex} = \beta * I_{ef}$ [Euro/year] (26)

Where: β represetnts the weight of annual expenses for pre-heater maintenance.

2.1. Annual expenses reduction

$C_{\Delta B} = \Delta B_{PA} * p_c$ =73288.08[Euro/year] (27)

P_c = 25 Euro/MWh

2.2. Annual expenses for pre-heater

$C_{PA} = 0.04 * I_{ef}$=3130.126 [Euro] (28)

$\Delta C_{PA} = C_{\Delta B} - C_{PA}$ =73288.08-3130.126 = 70157.96 [Euro/year] (29)

3. Payback period (without eco-taxes)

$$Tr_f = \frac{\Delta I_{PA}}{\Delta C_{PA}} = \frac{78253.15}{70157.96} = 1.1[years], \quad (30)$$

Generally, the payback period should be $T_r < T_{rn} = 2$ years (Trn – reference payback period for the energy efficiency measures regarding SER recovery).

For the conditions when the eco-tax for sulphur is applied (300 Euri/t SO2), the payback period is as follows:

$Tr_f^* = \Delta I_{PA} / \Delta C_{PA} + \Delta Ec$ = 78253,15/78558= 0,99[years], (31)

$\Delta Ec = \Delta SO_2 * 300$ [Euro]=28*300=8400 [Euro/year] (32)

$\Delta SO_2=85.48-57.55=28$ [t/year] (33)

5. Conclusions

The performed analysis can lead to the following conclusions:

- The complex analysis of the efficiency of SER recovery for a given contour is performed taking into consideration energy, environmental and economic aspects. The efficiency of the chosen solution is shown through calculation of the energy criteria (fuel savings, energy recovery degree), environmental criteria (environmental impact criteria) and economic criteria (payback period).
- The final decision regarding the implementation of the SER recovery solution is always taken only based on the economic criteria. The decision is more concluding when eco-taxes are used.
- The presented case study shows a relative fuel economy of Δb=32.4% and an energy recovery degree of δ_{PA} = 31%, which demonstrates the energy efficiency of the chosen solution.
- The environmental efficiency is shown through calculation of the environmental impact criteria. The calculated criteria show the decrease of annual emissions and other criteria for the chosen solution compared to the reference one.
- All these energy and environmental aspects have been taking into account when calculating the payback period, which is less than 2 years (nominal value for such energy efficiency projects).
- The payback period is less than 1 year for the case of applying eco-taxes, which shows that the efficiency of such a project increases once the environmental effects are internalised.

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