COST MODELS COMPARISON OF THE PRODUCTS GENERATED IN A COGENERATION POWER PLANT

Fabrício Ramos Del Carlo, fabríciodelcarlo@ig.com.br
José Antonio Perrella Balestieri, perrella@feg.unesp.br
UNESP – Universidade Estadual Paulista Júlio de Mesquita Filho
Faculdade de Engenharia – Departamento de Energia
Av. Ariberto Pereira da Cunha, 333 – 12516-410 – Guaratinguetá, SP

Abstract: *One of the most important questions regarding the cogeneration issue is the cost definition obtained through the operation of a certain configuration as a form to guarantee the viability of a certain enterprise. On this work it can be identified the real investment amount, operation, and maintenance on the main components of a combined cycle associated to an absorption cooling system and its equations based on energetic and exergy analysis concepts for an afterwards cost analysis based on different methodologies in order to state their advantages and disadvantages on cogeneration applications. Through the current study it is possible to consider a real evaluation using the data, which was obtained with some suppliers, based on traditional economic analysis models, in such a way that is possible to compare some of the cost allocation models described on the classic literature.*

Keywords: *cogeneration, exergetic analysis, trigeneration, exergoeconomic costs*

1. INTRODUCTION

The investment decisions among technical alternative designs and efficient use of the energy projects necessarily taken into account the economic feasibility analysis. This analysis is normally based in economic evaluation models, for which it is possible to determine the higher or lower attractiveness of an investment. Amongst the traditionally used techniques, the net present value (NPV) can be cited as one of the more important, as well as the internal tax of return (ITR); payback or time to return is not an economic model, although usually employed in economic analysis.

An important question for the definition of cogeneration attractiveness is the statement of the products costs obtained from the thermal cycle operation. As a cogeneration system presents two or more useful energy streams to be offered to the process, it is important to clearly define the proportion of each stream for guaranteeing the feasibility of certain enterprise.

2. CONCEPT OF COGENERATION

Cogeneration is an effective energy conservation method that can be applied when economically justified. The term cogeneration usually is assigned to the simultaneous generation of heat (steam, cold and hot water and/or air) and power (electric or mechanical) in installations of the tertiary and industrial sectors. The cogeneration rationality holds distinct visions, in accordance with the applications that it is destined.

The investment in cogeneration systems can be considered a positive alternative if compared with the current energy generation technology status, as is conceived the centralized system. In this, the electric energy necessities are taken care of by means of purchase contract with a concessionaire, being the thermal necessities (hot or cold) taken care of by means of self-production. The electric energy can also be self-produced, and in these cases the generation units must be dimensioned to operate independently of the electric grid for guaranteeing the isolated system reliability.

2.1. EXERGY MODELING

The energy (based on 1st Thermodynamics Law) and exergy (based on 2nd Thermodynamics Law) efficiencies for the analysis of flows and thermal components are directly related to the energy and exergy use, respectively. The exergy (B) is defined as the maximum reversible work produced between a system and the surrounding when they interact to reach the balance, that is, $B = W_{rev}$. Based on this, for the VC of Figure 1, the general exergy formularization is expressed in equation (2), simply by rearranging the terms of 1st Law equation (1).

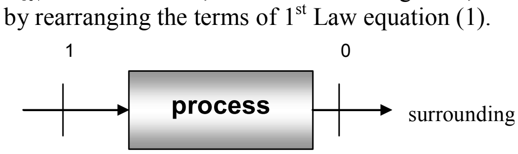


Figure 1. Control volume

$$T_0 ds - B\Big|_0^1 = E_s - E_e = h_0 - h_1 + \frac{V_0^2 - V_1^2}{2} + g(Z_0 - Z_1) \quad (1)$$

$$B\Big|_0^1 = h_1 - h_0 + \frac{V_1^2 - V_0^2}{2} + g(Z_1 - Z_0) - T_0(s_1 - s_0) \quad (2)$$

For the same process, in terms of mass flow, the "physical exergy" is defined in equation (3).

$$B^F\Big|_0^1 = \dot{m}[h_1 - h_0 + \frac{V_1^2 - V_0^2}{2} + g(Z_1 - Z_0) - T_0(s_1 - s_0)] \quad (3)$$

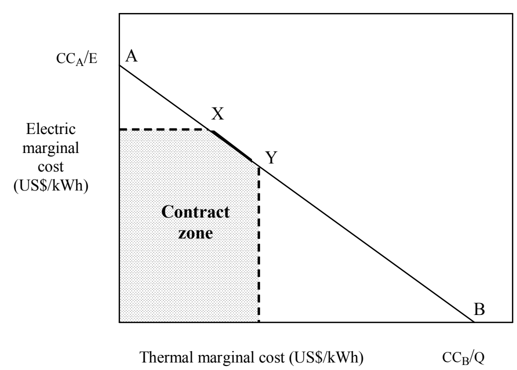
If kinetic parcel and potential parcels can be ignored, a simplified expression is then obtained for the physical exergy analysis, according to equation (4),

$$B^F\Big|_0^1 = \dot{m}[h_1 - h_0 - T_0(s_1 - s_0)] \quad (4)$$

According to Bejan *et al*. (1996), the accounting of costs in a company is related to the real value product costs determination and services, to the establishment of a rational basis for the same products prices definition and services, the definition of an allocation form, the control of the expenses and the provision of information for evaluation and decision-making.

The same authors declare that the rule of costs allocation between the different generated forms of energy in a cogeneration system is arbitrary. For the Figure 2, a thermoelectric power generation, for example, just produces electric power, and is representative of point A, a purely electric cost (Cw/E), i.e., no costs attributable to thermal flows; by the other side, a conventional steam generator just produces steam and is representative of point B, a purely thermal cost (CQ/Q), i.e., no costs attributable to electric/mechanical power.

For a cogeneration system that produces both electric/mechanical and thermal energy, the partition of costs among the values of points A and B, that represents the marginal costs[1] of electric/mechanical power and steam, respectively, is a point in the straight line with negative angular coefficient that crosses A and B, which allows different alternatives of thermal and electric partition costs. Contract zone is the region of reasonable thermal and electric/mechanical costs for a cogeneration system.



Source: Verbruggen (1983)

Figure 2 – "trade-off" curve for electric and thermal cots in cogeneration power plants.

For the Exergetic Cost Theory (ECT), the exergetic cost of each flow is obtained from a structure formed for a system, whose limits have been defined and with an aggregation level that specifies the subsystems composed by it.

The relation between "m" flows and "n" components is established by means of an incidence matrix (m, n); the elements a_{ij} of the matrix assume values +1 when flow j enters in subsystem i, -1 when flow j goes out subsystem i and 0 when physical relation between them does not exist (Valero and Lozano, 1993). For the association of the exergetic costs, 5 proposals are used (Lozano and Valero, 1993):

[1] Marginal costs (US$/kWh) they are the necessary values of investment (US$/h) so that certain capacity (kW) either installed.

Proposal 1: the exergy cost of a flow[2] (B*), Product (P*) or Fuel (F*) is the amount of necessary exergy for producing it, being therefore a conservative property. This proposal allows that as many exergy cost equations are formulated as components are available to compose the installation. Equation (9) presents this relationship by means of a matrix formulation:

$$\mathbf{A\ B^* = 0^*}. \qquad (5)$$

in which A is the incidence matrix, B* is the exergetic cost vector and 0* is the null vector. If there have “m” flows, it is necessary to establish “m” independent equations to find a solution of compromise between the variables; as the installation counts on “n” components, proposal 1 generates “n” independent equations, being necessary (m-n) equations for the solution. This set of equations is constructed with the n available equations for the n components of the installation.

Proposal 2: the entrance flows exergetic cost of the installation (fuel, air, water, etc.) are equal to their exergy.

If one or more output streams of a component are part of a incoming flow (F), it must be considered that its exergy unitary cost (B*/B) is identical to the unitary exergy cost of the entrance flow that is precedent.

Proposal 3: if one or more output streams of a component are part of incoming flow (F), it must be considered that its exergy unitary cost (B*/B) is identical to the unitary exergy cost of the entrance flow that precedes.

If a component has a product (P) formed by some flows, the same unitary exergetic cost must be associated with them. This is explained for the fact of that if 2 or more products they can exactly identified whit certain equipment, their formation processes are indistinct in the considered level of aggregation and therefore the exergetic cost must be associated proportionally to their exergy.

Proposal 4: if a component has a product (P) formed by some flows, the exergetic unitary cost associated with these flows are the same.

This is explained for the fact of that if 2 or more products they can exactly be identified with certain equipment, their formation processes are indistinct in the considered level of aggregation, and therefore the exergetic cost must be associated proportionally to their exergy.

Proposal 5: in the absence of external values to the losses flows (heat yielded to the environment, exhaust gases, amongst others), null exergetic cost must be attributed to them, since they do not present posterior utility.

2.2. TETRA-GENERATION SYSTEM ANALISYS

The present study aims at to consider a tetra-generation cycle for attendance of the electric energy demands, high-pressure steam, low pressure steam, hot water and cold water for an industry of hygienic disposable products that operates in thermal parity.

The industry demands 3.5 (kg/s) high pressure steam at 4 MPa and 360ºC to heat a set of debulkers[3], that is represented by the process A, also has the necessity of 3.0 (kg/s) of low pressure steam at 0.8 MPa and 205ºC for the hot glue production, represented for process B. The production of tissue paper demands 3.0 (kg/s) of hot water at 80ºC for the cleaning and conversion system, represented in this analysis by process C, and finally there is a demand of 3.71(kg/s) of cold water at 5ºC for the production of diapers and absorbents.

The industry under analysis consumes 40,000 kWh/month of electric energy, that also will have to be supplied partially or integrally by the cogeneration system; in the case of electric energy deficit, it is possible to buy the electric energy from a local electric concessionaire, and if some electric surplus is generated, it is possible to offer it for the same concessionaire.

Therefore, a cogeneration system based on a gas/steam combined cycle, composed by a gas turbine, a heat recovery steam generator, a condensation with extraction steam turbine, a mixture heater and an absorption refrigeration system is taken to be considered for attending the energetic demands and evaluation of generated products costs. The proposed cogeneration scheme (Figure 3) is capable of producing simultaneously electric power, superheated steam with two levels of pressure, hot water and cold water, what it is also known for “tetra-generation”.

[2] Unitary exergetic cost is defined as $k^* = B^*/B = 1/\eta$

[3] "Debulker" is a commonly used term to describe compression systems within the disposable consumer products industry.

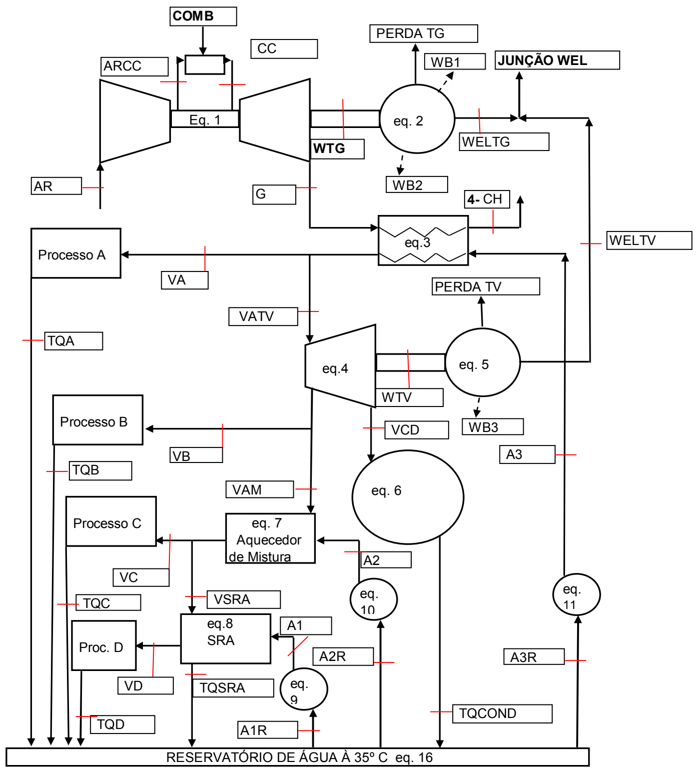


Figure 3 - Configuration considered for comparison of products costs

The following set of equations was proposed to model the cogeneration scheme according to Exergetic Cost Theory:

Proposal 1:

$Bar - Barcc + Bwcp = 0$ (5)
$Barcc - Bcc + Bcomb = 0$ (6)
$Bcc - Bg - Bwcp - Bwtg = 0$ (7)
$Bwtg - Bpertg - Bwb1 - Bwb2 - Bweltg = 0$ (8)
$Bg + Ba3 - Bch - Bva - Bvatv = 0$ (9)
$Btqa + Btqcond + Btqb + Btqc + Btqsra - Ba2r - Ba1r - Ba3r = 0$ (10)
$Bvatv - Bwtv - Bvcd - Bvb - Bvam = 0$ (11)
$Bwtv - BperTV - BwelTV - Bwb3 = 0$ (12)
$Bvam + Ba2 - Bvc - Bvsra = 0$ (13)
$Bvcd - Btqcond = 0$ (14)
$Ba1 + Bvsra - Bvd - Btqsra = 0$ (15)
$Ba1r + Bwb1 - Ba1 = 0$ (16)
$Ba2r + Bwb2 - Ba2 = 0$ (17)
$Ba3r + Bwb3 - Ba3 = 0$ (18)
$Bweltv + Bweltg - Beltot = 0$ (19)

Proposal 2:

$Bcomb = Ecomb$ (20)
$Bar = Ear$ (21)

Proposal 3 e 4:

$Bcc = (Ecc/Eg) * Bg$ (22)
$Bwb1 = (Ewb1/Ewb2) * Bwb2$ (23)
$Bwb1 = (Ewb1/Eweltg) * Bweltg$ (24)
$Bcomb = (Ecomb/Earcc) * Barcc$ (25)

Bva = (Eva/Evatv) * Bvatv (26)
Bvatv=Evatv*((Bvb+Bvcd+Bvam)/(Evb+Evcd+Evam)) (27)
BwelTV = (EwelTV/Ewb3) * Bwb3 (28)
Bvc = (Evc/Evsra) * Bvsra (29)
Bvsra = (Evsra/Etqsra) * Btqsra (30)

Proposal 5:

Bpertg = 0 (31)
Bpertv = 0 (32)
Bch = 0 (33)

Absorption:

Ba1 = (Ea1/Ea1r) * Ba1r (34)
Ba2 = (Ea2/Ea2r) * Ba2r (35)
Ba3 = (Ea3/Ea3r) * Ba3r (36)
Btqa =(Etqa/Eva)*Bva (37)
Btqb =(Etqb/Evb)*Bvb (38)
Btqc =(Etqc/Evc)*Bvc (39)
Btqd =(Etqd/Evd)*Bvd (40)
Bvam =(Evam/Ea2)*Ba2 (41)

The fuel energy was estimated by means of equation (42).

$$\dot{E}_{Comb} = \dot{m}.PCI \ \text{(kW)} \quad (42)$$

The values relative to the Energy (E) present in table 1is calculated through equation (43):

$$\dot{E} = \dot{m}(h - h_0) \ \text{(kW)} \quad (43)$$

The definition of fuel and exhaust gases exergetic values were composed in two parcels, being a physical and a chemical one. For the fuel exergy value, a coefficient[4] was applied to the energy of fuel, for simplicity, as follows in equation (44).

$$\dot{B}_{Comb} = \dot{E}_{Comb}.1.04 \ \text{(kW)} \quad (44)$$

The gases proceeding from the fuel burning were calculated through the equations (45) and (46), the first considering the physical parcel of the gases and second one considering the chemical parcel of the gases.

$$\dot{E}_g = \dot{m}_g.cp_g.(T - T_0) \ \text{(kW)} \quad (45)$$

$$\dot{B}_g = \dot{m}_g.\left(cp_g.\ln.\frac{T_g}{T_0} - R.\ln\frac{P_a}{P_b} \right) \ \text{(kW)} \quad (46)$$

The gases proceeding from the compression were calculated through the equation (47).

$$\dot{B}_{ARCC} = \dot{m}_{AR}.\left(cp_{AR}.(T_{ARCC} - T_0) - T_0.\left(cp_{AR}.\ln\frac{T_{ARCC}}{T_0} - R.\ln\frac{P_{ARCC}}{P_0} \right)\right) \quad (47)$$

The gases proceeding from the mixture air-fuel burning in the combustor are calculated through the equation (48).

[4] The value of 1.04 relative to the chemical parcel of the fuel exergy refers to natural gas (from Kotas, 1985, p. 269).

$$\dot{B}_{CC} = \dot{m}_{CC} \cdot \left(cp_G \cdot (T_{CC} - T_o) - T_0 \cdot \left(cp_G \cdot \ln \frac{T_{CC}}{T_0} - R \cdot \ln \frac{P_{CC}}{P_0} \right) \right) \quad (48)$$

For the physical exergy calculation of the flows present in the configuration it was considered the equation (49):

$$\dot{B} = \dot{m}[(h - h_0) - T_0(s - s_0)] \ \text{(kW)} \quad (49)$$

Other points to be defined are related to the thermodynamic sizing of the compressor of the gas turbine. For a commercial gas turbine, the following equations were used to determine some parameters for the physical model.

- air compressor: $$T_2 = T_1 \left\{ 1 + \frac{1}{\eta_{cp}} \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \right\} \quad (50)$$

- combustion chamber: $$P_3 = P_2 (1 - \Delta P_{cc}), \quad \Delta P_{cc} \cong 0{,}05 \quad (51)$$

- gas turbine: $$T_4 = T_3 \left\{ 1 - \eta_{tg} \left[1 - \left(\frac{P_4}{P_3} \right)^{\frac{n-1}{n}} \right] \right\} \quad (52)$$

The power consumed for the compressor drive was given by the equation (53).

$$\dot{W}_{CP} = \dot{m}_{AR} \cdot cp_{AR} \cdot (T_{CC} - T_0) \quad (53)$$

2.3. RESULTS

For the application of the ECT, the mass conservation modeling must be initially applied, followed by energy and exergy balances; in the matrix form, the calculation of the exergetic costs (B*) and exergoeconomics costs (P) can be done through equations (54) and (55):

$$\left[\frac{A}{\alpha} \right] B^* = \left[\frac{0}{\omega} \right] = \underline{Y}^* \Rightarrow B^* = \underline{A}^{-1} \underline{Y}^* \quad (54)$$

$$\left[\frac{A}{\alpha} \right] \Pi = \left[\frac{-Z}{\omega_Z} \right] = \underline{Z}^* \Rightarrow \Pi = \underline{A}^{-1} \underline{Z} \quad (55)$$

Table 1 presents the thermodynamic parameters of the tetra-generation scheme proposed (Figure 3); Table 2 presents the vector Y, that contains the right-side values of the set of 37 equations considered in the ECT modeling, and the results of the multiplication of the inverse matrix A by the Y vector; Table 3 presents the values of the unitary exergetic costs of the proposed configuration.

Table 4 demonstrates the investment cost for the composition of the proposed configuration and Table 5 presents the values of the exergoeconomic costs for the same project.

3. CONCLUSION

In this paper, a cogeneration system was considered for the case study relative to a manufacturer whose purpose is to produce diapers, absorbents and tissue paper. This industry demands electric energy, high pressure steam, low pressure steam, hot water and cold water for attending its production processes. At this time, thermal flows are self-generated and electricity is purchased from the local grid. In such a way, a cogeneration system (a tetra-generation system) was proposed to produce simultaneously the thermal and electric demands.

The electric energy purchase tariff in São Paulo State for an industry is 0.085 (US$/kWh) on average. According to some contracts reviewed, a cogeneration system electric energy produced is valued around 75% or less than the electric energy purchase tariff.

The electric energy average cost of tetra-generation system was of 0.071 (US$/kWh). The energy thermal values were based on real values of an industrial company therefore does not have a market reference for comparison of the sales of steam, hot water and cold water. The thermal energy average value in cogeneration system is of 0.1364 (US$/kWh). These values were obtained through the application of the ECT method, whose results are demonstrated in table 3.

Table 1. Thermodynamics parameters.

	fluxo	m(kg/s)	x	P (MPa)	T (o C)	h (kJ/kg)	s(kJ/kgK)	E (kW)	B (kW)
AR	1	166,93		0,1	25	104,6	0,37	0	5
ARCC	2	166,93			428				-74159
CC	3	169,6		2,29	1103				-163659
Comb	4	2,67							133709
G	5	169,6			458				32298
CH	6	169,6			101				1622
WCOMPR	7								57954
WTG	8								50870
VATV	10	4,01		4	360	3117	6,62	12080	4607
VA	11	3,5		4	360	3117	6,62	10543	4021
TQA	12	3,5		0,1	24,5	103	0,36	-6	1
WTV	13							1489	1489
VCD	14	1	0,87		33	2247	7,36	1500	40
VB	16	3		0,8	205	2851	6,84	8239	2453
TQB	17	3		0,1	24,5	103	0,36	-5	1
VAM	18	0,31		0,8	205	2851	6,84	851	253
TQCOND	19	0,7		0,09	33	188,5	0,60	59	10
A2	20	4,37		6	35	152	0,50	207	30
A2R	21	4,37		0,01	35	146,7	0,50	184	6
A1R	22	3,71		0,01	35	146,7	0,50	156	5
A1	23	3,71		6	35	152	0,50	176	26
VSRA	25	1,68			80	335	1,08	387	33
VC	26	3			80	335	1,08	691	59
TQC	27	3		0,1	24,5	103	0,36	-5	1
VD	28	3,71			5	20,98	0,06	-310	26
TQD	29	3,71		0,1	24,5	103	0,36	-6	1
A3	30	7,51		6	35	152	0,50	356	52
A3R	31	7,51		0,01	35	146,7	0,50	316	9
WB1	32							-20	-20
WB2	33							-19	-19
WB3	34							-40	-40
TQSRA	35	1,68		0,1	24,5	103	0,36	-3	1
Perda TG	36							2544	2544
Perda TV	37							74	74
WELTV	38							1415	1415
WELTG	39							48327	48327
WELtotal	40							49741	49741

Table 2. Mult. Matrix

	Y*	B*=(A-1)x(Y*)
1	0	5
2	0	74159
3	0	207868
4	0	133709
5	0	41023
6	0	1622
7	0	74154
8	0	92691
9	0	21188
10	0	18493
11	0	5
12	0	8557
13	0	40
14	0	12210
15	5	4
16	133709	381
17	1622	40
18	0	46
19	0	9
20	0	8
21	0	46
22	0	153
23	0	274
24	0	4
25	0	197
26	0	9
27	0	281
28	0	47
29	0	38
30	0	36
31	0	234
32	0	2
33	0	0
34	0	0
35	0	8322,778681
36	0	92616,63923
37	0	100939,4179

Table 3. Exergetic Costs

k*	k* (por ano	n=1/k*
1,00	2,17	1,00
1,00	2,17	1,00
1,27	2,75	0,79
1,00	2,17	1,00
1,27	2,75	0,79
1,00	2,17	1,00
1,28	2,77	0,78
1,82	3,95	0,55
4,60	9,97	0,22
4,60	9,97	0,22
4,60	9,97	0,22
5,74	12,45	0,17
1,00	2,16	1,00
4,98	10,79	0,20
4,98	10,79	0,20
1,50	3,26	0,66
4,11	8,91	0,24
1,50	3,26	0,66
1,50	3,26	0,66
1,80	3,90	0,56
1,80	3,90	0,56
4,67	10,12	0,21
4,67	10,12	0,21
4,67	10,12	0,21
7,60	16,46	0,13
7,60	16,46	0,13
5,37	11,63	0,19
5,37	11,63	0,19
1,92	4,15	0,52
1,92	4,15	0,52
5,88	12,74	0,17
4,67	10,12	0,21
0,00	0,00	#DIV/0!
0,00	0,00	#DIV/0!
5,88	12,74	0,17
1,92	4,15	0,52
2,03	4,40	0,49

Table 4. Investment costs with equipment

Equipamento	Z
	0
	0
TG	-0,49501
GERADOR TG	-0,15793
CR	-0,29010
TV	-0,24729
GERADOR TV	-0,02183
COND	-0,00427
AM	-0,00356
SRA	-0,00356
B1	-0,00071
B2	-0,00071
B3	-0,00071
TANQUE	-0,00036
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0

Table 5. Results of the exergoeconomics values

	($/GJ)	Pi ($/s)	$/kWh
AR	0,00	0,00	0
ARCC	0,00	0,00	0
CC	0,00	0,00	0
Comb	0,00	0,00	0
G	0,00	0,00	0
CH	0,00	0,00	0
WCOMPR	0,00	0,00	0
WTG	9,73	0,50	0,035031
VATV	34,99	0,16	0,125976
VA	34,99	0,14	0,125976
TQA	34,99	0,00	0,125976
WTV	209,74	0,31	0,75506
VCD	73,45	0,00	0,264433
VB	36,25	0,09	0,130501
TQB	36,25	0,00	0,130501
VAM	40,03	0,01	0,144096
TQCOND	135,81	0,00	0,488933
A2	40,03	0,00	0,144096
A2R	40,03	0,00	0,144096
A1R	46,07	0,00	0,165849
A1	46,07	0,00	0,165849
VSRA	163,23	0,01	0,587636
VC	163,23	0,01	0,587636
TQC	163,23	0,00	0,587636
VD	385,88	0,01	1,38918
TQD	385,88	0,00	1,38918
A3	226,02	0,01	0,813661
A3R	226,02	0,00	0,813661
WB1	13,50	0,00	0,048601
WB2	13,50	0,00	0,048601
WB3	229,74	0,01	0,827077
TQSRA	163,23	0,00	0,587636
Perda TG	0,00	0,00	0
Perda TV	0,00	0,00	0
WELTV	229,74	0,33	0,827077
WELTG	13,50	0,65	0,048601
WELTOT	19,65	0,98	0,070746

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5. RESPONSIBILITY NOTICE