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# Theoretical Exergoenvironmental Analysis of a Tunnel Furnace and Drying System in a Brick Production

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**Highlights**

- This paper focuses on sustainability of brick production in a tunnel furnace and a tunnel dryer.
- Real brick production data were used.
- Exergoeconomic and exergoenvironmental analyses were done.

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**Abstract**

The performance of a tunnel furnace and a tunnel dryer in a brick production was exergoenvironmentally assessed. The real production data of a brick factory in Turkey with a daily production capacity of 392 tons of fired bricks were used in the analysis. The exergoenvironmental factor of the control volume was calculated as 0.87. The specific exergoenvironmental cost of the control volume was determined to be 559.55 €/h, 3.39 €cent/ kg fired brick and 1.94 €cent/MJ. The specific exergoeconomic cost and the environmental damage prevention cost were obtained to be 0.41 € cent/MJ and 1.53 € cent/MJ, respectively. Because the ratio of exergoenvironmental cost to sales price of 2.41 € cent / kg fired brick was 1.41 (above 1), it was concluded that the brick production in Turkey was not sustainable in terms of exergoenvironmental analysis.

## 1. INTRODUCTION

Efforts for the prevention of climate change are needed more than ever. Production systems that degrade the environment with low efficiencies and waste emissions cannot be regarded as sustainable. When the products are produced with less exergy than the environmental damage due to less waste emissions will be reduced [1]. The exergetic destructions may be accepted as useful although they result low exergetic efficiency [2]. In a rotary kiln used for plaster production, the exergetic efficiency of the thermal process was reported as 16%. Preheating stages used in the thermal process led to energy savings up to 0.11 GJ/ton product corresponding to a saving of 9.3kg $CO_2$/ton product [3].

For the reduction of harmful emissions, biomass can be contributed to the fuel. Biomass consumes more $CO_2$ before its harvest and usage as a fuel. Thefore, its eco indicator value, which shows its environmental damage, is negative [4]. Among the biomass types of paper, municipality solid waste, paddy husk, and wood; wood was reported to yield the least $CO_2$ emission [5]. Engaging a Stirling engine to a gas turbine power systemdecreased the CO2 emission rates by 47.56%, 48.25%, 49.23%, and 37.81% for wood, paper, paddy husk, and MSW, respectively [5].

Another way of reduction of waste emissions to increase the exergetic efficiency is to cooperate renewable exergy sources into the control volume. When the heat pump drying was replaced with a solar assisted heat pump drying, the exergy efficiency of the drying cabin increased from 14.09 % to 22.78% [6].

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The levelized cost of electricity (LCOE) for asolar-aided biomass-fired combined heat and power system was 0.1306 $/kWh, which was lower than solar only thermal power plant. On the other hand, this LCOE value was higher than the LCOE range of a coal fired power plant, which was between 0.0478$/kWh and 0.0548 $/kWh [7].

The unit exergoeconnomic costs of electricity produced from PV, coal and natural gas were reported as 0.045, 0.04, and 0.02 US$/kWh, respectively. The unit environmental impact of grid electricityproduced from coal of grid electricity was 107.7 5 mPts/kWh which was much higher than the environmental impact of natural gas with 23.5 mPts/kWh [8].

Rather than environmental impact points, environmental damage prevention cost, which is the cost of replacement of the conventional energy system emitting emissions with the renewable energy system, can be used in the exergoenvironmental analysis of the brick production control volume [9]. It was stated that the environmental cost of a magnesite-spinel refractory brick production reached 83.9 % of its overall production cost [10]. The exergy efficiency values of two high temperature tunnel kilns firing refractory bricks were reported as 26% and 32%, respectively [11]. When heat could be recovered from flue gas, energy need to produce bricks could be reduced by 30% [12]. The degree of sustainability of a production process was measured by the criteria, such as total energy content, consumption of the environment, emissions, raw material, waste generation, recyclability, capital and durability [13].

The main objective of this research is to find out whether the operation of the control volume is exergoenvironmentally sustainable or not. The sustainability check loop was proposed to clarify long term feasibility of the control volume consisting of a tunnel dryer and a tunnel furnace. The tunnel furnace is one of the most efficient kilns used in brick production with a specific energy consumption range of 1.1-2.5 MJ/kg fired brick [14]. Although the investment cost is high in tunnel furnace structure, the net benefit is the highest when the environmental costs are considered [15]. The actual operational data of a brick factory were used for the exergoenvironmental analysis.

## 2. SYSTEM DESCRIPTION AND DATA USED

The control volume includes an 85m long, 15 m wide and 5 m high tunnel dryer and a 116m long, 4.6 m wide and 2.95 m high tunnel furnace. A schematic of the control volume studied is shown in Figure 1.

The control volume was used to dry and fire bricks made of clay. The wet brick bodies were entering the dryer placed on metal palettes suspending on metal dryer cars. The drying period was 26 hours. The heat required for the drying process recovered from the tunnel furnace whose fuel was crushed coal with an exergy of 25384.34 kJ/kg. The coal was injected from the 108 holes on the ceiling of the tunnel furnace. The air was sucked from the exit of the tunnel furnace with counter pressure fans and exhausted to the atmosphere through the kiln chimney located in the entrance of the kiln. While this ambient air was heated by the hot bricks, it recovered the heat required for the dryer and cooled down the fired bricks. The heat recovered from the furnace entered the dryer from the center top of the dryer and spread to the whole dryer with 96 accelerating fans. 64 of these fans were axial fans located inside the dryer and 32 of these fans were rotary fans located on top of the dryer. The humid air was exhausted from the two exhaust fans located at the entrance of the dryer. The dried brick bodies were set on to kiln cars to be fired for 22 hours. The firing capacity of the control volume was 16503.84 kg/h.

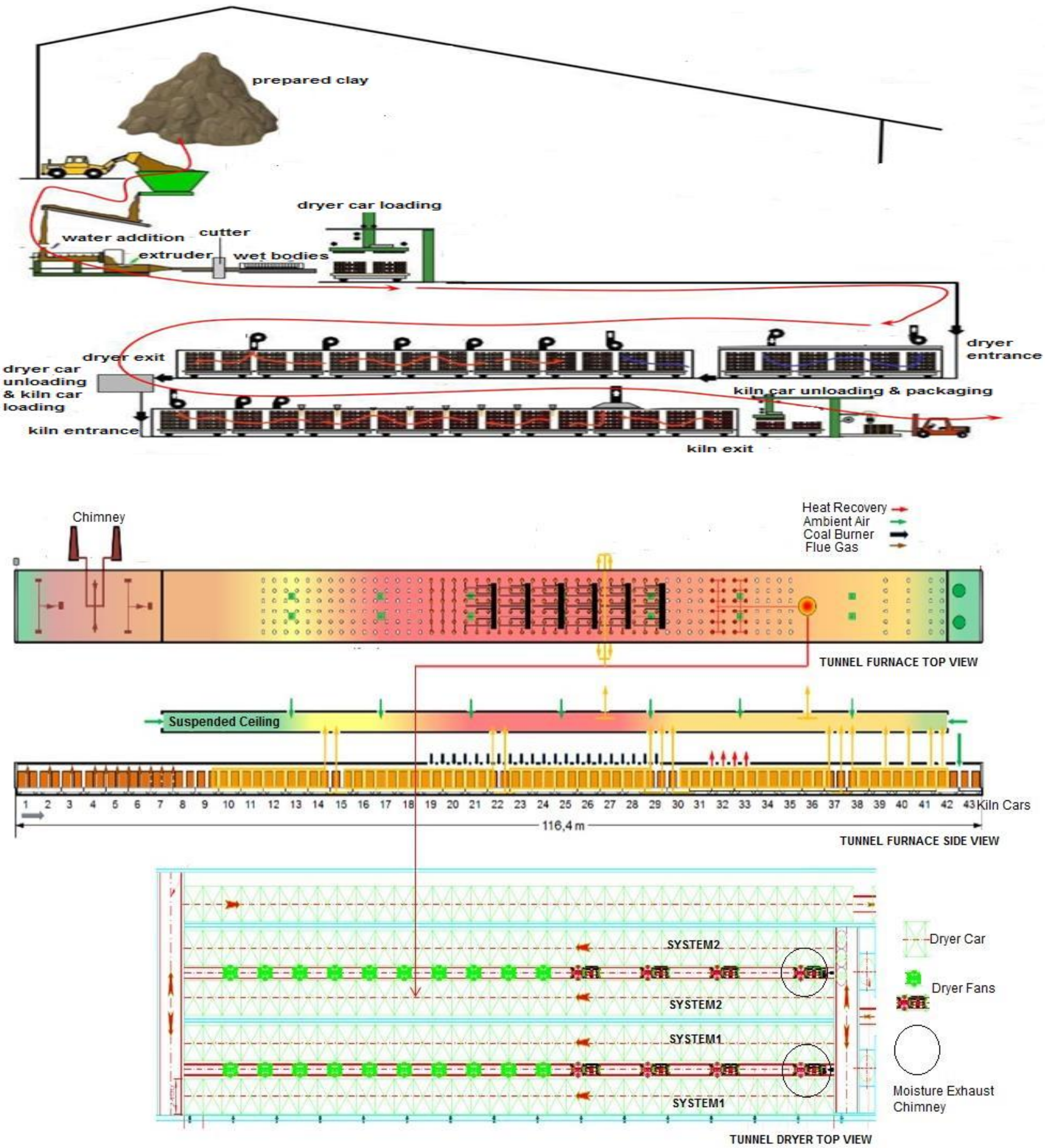


***Figure 1.*** *Control volume of the tunnel furnace and tunnel dryer system studied [2]*

The exergy and energy efficiency values of the control volume were obtained to be 12.90% and 76.46% from the previous study of the authors [2]. The exergy analysis diagram is illustrated in Figure 2. The irreversibility rate, defined as the difference between the exergy input rates and exergy output rates of control volume, was determined as 6971 kW. 1756 kW of this irreversibility rate was caused by the exergy destruction for the evaporation of water content of the wet brick bodies, 658 kW was destructed for the firing of brick, 3759 kW was destructed for the firing of dried brick bodies, 129kW was destructed for the evaporation of coal moisture, 189kW of electrical power was destructed for maintaining even air temperature inside the dryer.

The exergy rates of the input streams of coal, electrical work transfer, air and clay body were 7575 kW, 372 kW, 53 kW and 3 kW, respectively. The exergy rates of the exit streams of ash on the kiln car, flue gas, dried brick bodies and fired bricks were determined as 830 kW, 103kW, 90 kW, 5 kW and 4 kW, respectively [2].

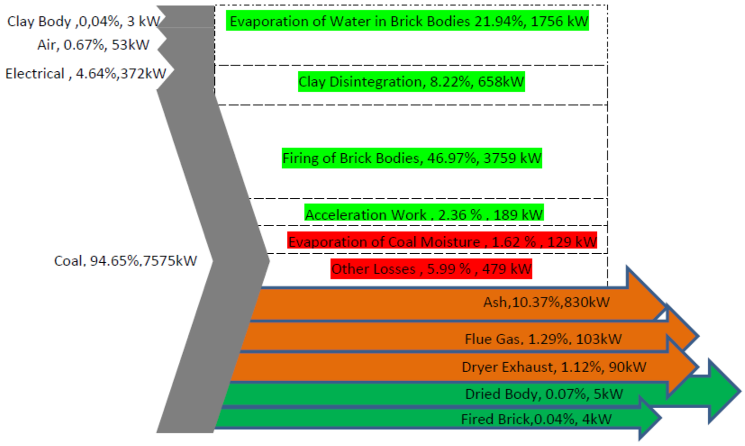


***Figure 2****. Exergies of the streams entering and exiting the control volume [2]*

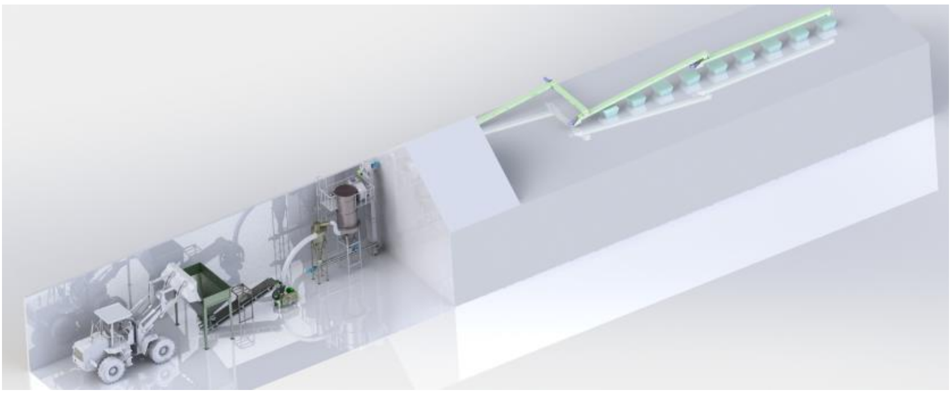

***Figure 3****. The coal crusher system*

***Table 1.*** *Production and unit cost data for input exergy streams*

| **Description** | **Quantity** |
|---|---|
| Clay Body | 17392 kg/h |
| Fired brick | 16504 kg/h |
| Consumed coal | 30.73tons/day |
| Exergy of coal | 25384kJ/kg |
| Coal crusher capacity | 5 tons/h |
| Coal crusher electrical exergy rate | 59.69kW |
| Coal cost | 38.09€/ton |
| Electricity cost | 65.30€/MWh |
| Clay cost | 1.35€/ton |
| Air cost | 0€/ton |

The fuel of the control system was crushed coal. The crusher system is shown in Figure 3. Two different types of coals were mixed equally. The production and unit cost data of the input streams are given in Table 1.

The average cost of materials consumed for the operation and maintenance of the control volume is given in Table 2. The three-year average cost of materials used for the operation and maintenance of the control volume was determined as 23895 € annually.

***Table 2.*** *The cost of materials consumed for the operation and maintenance of the control volume*

| **Years** | **2016** | **2017** | **2018** | **Average** |
|---|---|---|---|---|
| Material Cost (€) | 26804 | 23394 | 21487 | 23895 |

The labor required for the operation and maintenance of the control volume is listed in Table 3. Kiln operators, firemen, electrical and mechanical technicians were employed for the operation and maintenance of the control volume.

***Table 3.*** *The cost of labor used for the operation and maintenance of the control volume*

| **Labor Type** | **Quantity** | **On Duty Ratio** | **Occupied Quantity** | **Average Salary €** | **Annual Cost €** |
|---|---|---|---|---|---|
| Kiln operator | 4 | 1/1 | 4 | 482 | 23114 |
| Fireman | 4 | 1/1 | 4 | 434 | 20803 |
| Electrical technician | 6 | 1/3 | 2 | 578 | 13868 |
| Mechanical technician | 11 | 1/4 | 2.75 | 530 | 17480 |
| Total Labor | | | 12.75 | | 75265 |

***Table 4.*** *Emissions from the kiln chimney and the two dryer chimneys of the control volume*

| **Emission Type** | **Mass Flow Rate (kg/h)** |
|---|---|
| CO | 3.68 |
| $CO_2$ | 1273.43 |
| NO | 0.76 |
| $NO_2$ | 1.16 |
| $SO_2$ | 9.17 |
| Dust | 5.44 |

***Table 5.*** *The cost for the prevention of damage given by emissions*

| **Emisson Type** | **Specific Environmental Damage Prevention Cost ( €/kg )** |
|---|---|
| CO | 0.174 |
| $CO_2$ | 0.116 |
| NO | 11.720 |
| $NO_2$ | 11.720 |
| $SO_2$ | 8.750 |
| Dust | 35.00 |

The occupied portion of the kiln operators, firemen, electrical operators, and mechanical operators were 1/1, 1/1, 1/3 and 1/4, respectively. The total labor cost of the control volume was calculated as 75265 € annually. Emissions from the kiln chimney and the two dryer chimneys of the control volume were measured by a flue gas analyzer. The measured emissions are shown in Table 4 while the costs for the prevention of damage given by emissions taken from ECOCOST 2021-2022 [9] are given in Table 5.

## 3. ANALYSIS

The exergoenvironmental cost rate of the control volume is composed of two components [1,12]:

$$\dot{C}_{exen}=\dot{C}_{ex}+\dot{C}_{env} \tag{1}$$

where $\dot{C}_{ex}$ is exergoeconomic cost rate of the control volume and $\dot{C}_{env}$ is environmental damage prevention rate of the control volume.

The exergoeconomic balance of the control volume can be written as [1,16-18]

$$\dot{C}_{ex} = \sum_k \dot{C}_{out,k} + \sum_k \dot{C}_{d,k} + \sum_k \dot{C}_{l,k} = \sum_k \dot{C}_{in,k} + \dot{C}_q + \dot{C}_{w,k} + \dot{Z} \qquad (2)$$

where

$\dot{C}_{out,k}$ : The cost rate of the output exergy streams of the control volume,
$\dot{C}_{d,k}$: The cost rate of the destructed exergy in the control volume,
$\dot{C}_{l,k}$: The cost rate of the lost exergy in the control volume,
$\dot{C}_{in,k}$: The cost rate of the input exergy streams of the cntrol volume,
$\dot{C}_{q,k}$ : The cost rate of the heat exergy transferred into the control volume,
$\dot{C}_{w,k}$ : The cost rate of the work transferred into the control volume,
$\dot{Z}$ : The cost rate of the capital in the control volume.

The right hand side components of Equation (2) can be written for the control volume as

$$\sum_k \dot{C}_{in,k} = \dot{C}_{coal} + \dot{C}_{clay} + \dot{C}_{air} \qquad (3)$$

$\dot{C}_{coal}$, $\dot{C}_{clay}$ and $\dot{C}_{air}$ are the exergy cost rate of the coal, clay and air streams of the control volume

Exergy cost rates of the clay and air were ignored.

The exergy cost rate of the coal is the sum of cost of the coal exergy and the cost of the exergy consumed in the coal crusher system

$$\dot{C}_{coal} = c_{coal} * \dot{Ex}_{coal} + c_{elec} * \dot{W}_{crusher} \qquad (4)$$

where $c_{coal}$ and $c_{elec}$ are the cost of coal and electrical exergy, respectively while $\dot{Ex}_{coal}$ is the exergy rate of the coal used and $\dot{W}_{crusher}$ is the exergy rate of the electrical work consumed in the coal crusher system.

Since there is no heat transfer into the control volume

$$\dot{C}_q = 0. \qquad (5)$$

The cost rateof the electricity work transferred to the control volume is[1,17];

$$\dot{C}_{w,k} = c_{elec} \sum_k \dot{W}_{k,elec} \qquad (6)$$

where $c_{elec}$ is the cost of the electrical exergy and $\sum_k \dot{W}_{k,elec}$ is the sum of the electrical work transfer rates into the control volume.

The cost rate of the capital $\dot{Z}$has two components [1,17]:

$$\dot{Z} = \dot{Z}_k^{CI} + \dot{Z}_k^{0M} \qquad (7)$$

where $\dot{Z}_k^{CI}$ is the rate of capital invested in the control volume and $\dot{Z}_k^{0M}$ is the rate of capital consumed for the operation and maintenance of the control volume.

The present worth value of the control value can be calculated as [1,17];

$$P\dot{W}_{cv} = \dot{C}_{cv} - \dot{S}_{cv}PW_{cv}(i,n) \quad (8)$$

where $P\dot{W}_{cv}$ is present worth rate of the control volume, $\dot{C}_{cv}$ is cost rate of the investment value of the control volume and $\dot{S}_{cv}$ is salvage value rate of the control volume.

To calculate the cost of the investment value of the control volume from the cost of another control volume with a different capacity [1,17], we can use the following:

$$C = C_0\left(\frac{X}{X_0}\right)^{\alpha} \quad (9)$$

where $C_0$ is the investment cost of the control volume with the capacity of $X_0$, $C$ is the investment cost of the control volume with the capacity of $X$ and αis the scaling exponential, which can be taken as 0.6 [17].

The rate of annual cost of investment of the control volume can be calculated from [1,17]

$$\dot{CA} = P\dot{W}_{cv}CRF \quad (10)$$

$$CRF=\frac{[i(1+i)^n]}{[(1+i)^n-1]} \quad (11)$$

where *CRF* is the cost rate factor, $i_n$ is the nominal interest rate and *r* is inflation rate, *i* is the real interest rate and *n* is the lifetime of control volume in years.

The *R* coefficient is defined as the ratio of exergy loss rate in the control volume to the annual investment rate [1,17],

$$R=\frac{\dot{Ex}_{loss}}{\dot{CA}} . \quad (12)$$

The cost of the prevention of the damage given to the environment due to the emissions from the control volume $\dot{C}_{env}$ in €/h [1,12]:

$$\dot{C}_{env}=c_{CO}\dot{m}_{CO} + c_{CO_2}\dot{m}_{CO_2} + c_{SO_2}\dot{m}_{SO_2} + c_{NO}\dot{m}_{NO} + c_{NO_2}\dot{m}_{NO_2} + c_{PM2.5}\dot{m}_{PM2.5} \quad (13)$$

where $c_{CO}$, $c_{CO_2}$, $c_{SO_2}$, $c_{NO}$ , $c_{NO_2}$ and $c_{PM2.5}$ are the specific costs of prevention of damage given to the environment by the gases CO , $CO_2$, $SO_2$, NO , $NO_2$ and dust in (€/kg ) while $\dot{m}_{CO}$ , $\dot{m}_{CO_2}$, $\dot{m}_{SO_2}$, $\dot{m}_{NO}$ , $\dot{m}_{NO_2}$ and $\dot{m}_{PM2.5}$ are the mass rates of $CO$ , $CO_2$, $SO_2$, $NO$ , $NO_2$ gases and dust in kg/h.

The exergoenvironmental factor $f_{ei}$ [17]

$$f_{ei} = \frac{\dot{Ex}_d}{\sum \dot{Ex}_{in}} \quad (14)$$

with

$\dot{Ex}_d$ = The exergy destruction rate in the control volume,
$\dot{Ex}_{in}$ = The exergy rate of input streams in the control volume,
Environmental damage impact factor $\theta_{ei}$ [17]

$$\theta_{ei} = f_{ei} . cf_{ei} \quad (15)$$

with the coefficient of exergoenvironmental impact $cf_{ei}$ [17] is calculated from

$$cf_{ei} = \frac{1}{\mathcal{E}} \tag{16}$$

where Ɛ is the exergetic efficiency of the control volume.

The parameter $\theta_{eii}$ shows the enhancement in the coeeficient of exergoenvironmental impact, as written below [17]:

$$\theta_{eii} = \frac{1}{\theta_{ei}} \tag{17}$$

## 4. RESULTS AND DISCUSSION

With an assumption of a 15% bargain margin from the price of the turnkey control volume manufacturer, the cost of investment of the control volume was calculated as 5303425 €. The present worth of the control volume was determined to be 4773083 € with an assumption of its salvage value was 10% of the cost of its investment value.

When the interest rate and the annual interest rate for TL were taken as 19% and 16.59%, respectively and the lifetime of the control volume was assumed to be 50 years, the CRF coefficient was calculated as 0.0319.

The annual cost rate of investment $\dot{C}A$ was calculated as 152311 €. Since the output exergy is not used, it can be regarded as waste exergy. The graph of R coeffiecient is shown in Figure 4.

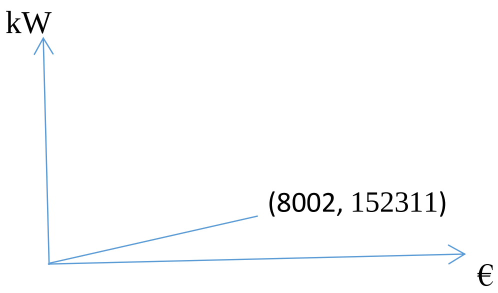


***Figure 4****. The graphical representation of R coeefcient (kW, €)*

The most of the electrical maintenance cost was caused by the replacement of the electrical motors in the dryer of the control volume. The high temperature in the dryer was the main reason for electrical motor damages since the electrical motors were installed inside the dryer, as shown in Figure 5. The maintenance hours increased in summer when the temperature was higher. The dust in the dryer disturbed the isolation of electical motors with the effect of high air recirculation. Another price paid for the high temperature in the dryer was the corrosion of metalwork inside the dryer.

***Figure 5.*** *The axial and rotary fans in the dryer*

The majority of the mechanical maintenance occured from the frequent repair need of the kiln cars. The bricks and the metal moldings used in the kiln cars were damaged from the hot and cold cycle and the high pressure pushing encountered in the production.The repair process of the kiln cars is shown in Figure 6. The cracked bricks and the broken metal moldings were replaced with the new ones during the maintenance of the kiln cars.

The annual cost of material used in maintenance of the control volume was determined as 23895 € and the annual cost rate of labor used in the operation and maintenance of the control volume was observed as 72809 €. Since the control volume was in operation in 365 days and 24 hours, the total annual cost rate of investment and operation and maintenance of the control volume was calculated as 28.43 €/h.

The cost of total input exergy to the control volume was determined as 118.12 €/h, which corresponded to 0.72 € cent/kg fired brick with the production of 16504 kg/fired brick. The exergoeconomic cost of the control volume was found to be 0.41 €cent/MJ, which was calculated as the ratio of the cost of input exergy rate to the total input exergy rate of 8002 kW.

The cost of prevention of damage given to the environment by the greenhouse gases and dust emitted from the control volume was calculated as 441.43 €/h, which corresponded to 2.67 €cent/kg fired brick and 1.53 €cent/MJ. The exergoenvironmental damage analysis is shown in Figure 7.

The exergoenvironmental cost of the control volume was calculated as 559.55 €/hr, 3.39 €cent/kg fired brick and 1.94 €cent/MJ.

***Figure 6.*** *The repair and maintenance of kiln cars*

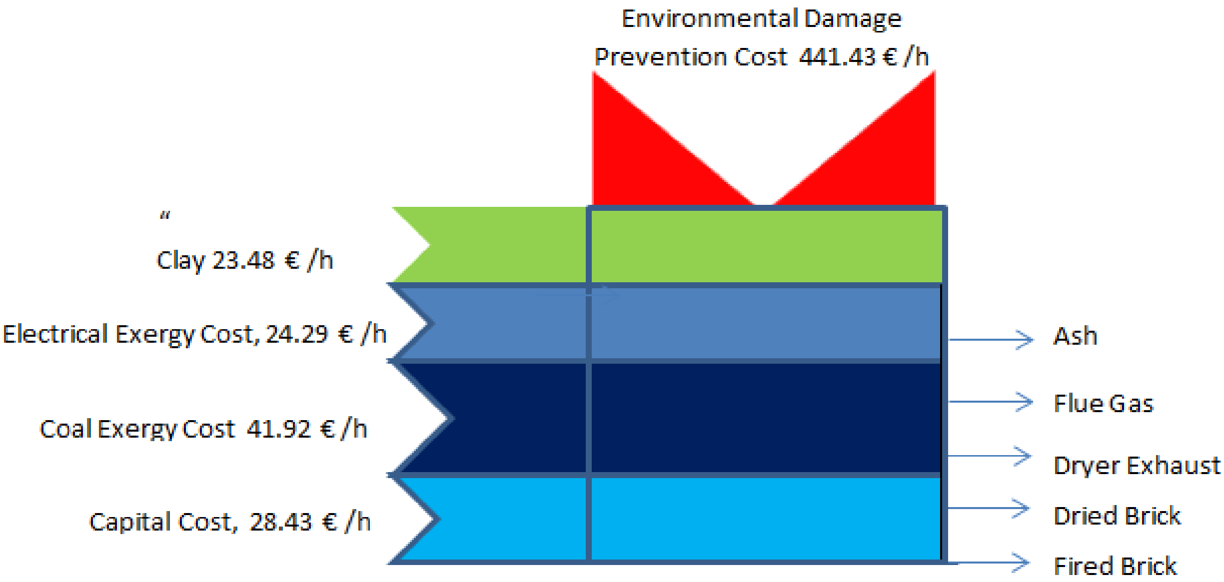


***Figure 7.*** *Exergoenvironmental analysis values*

Since 6971 kW of the input exergy rate of 8002 kW was destructed, the exergoenvironmental factor $f_{ei}$ was obtained to be 0.87. Environmental damage impact factor $\theta_{ei}$ was found as 6.74, which indicated high environmental damage impact. The parameter $\theta_{eii}$ showing the enhancement in the coeeficient of exergoenvironmental impact was calculated as 0.15, which meant low enhancement possibility. The environmental performance factors ($f_{ei}$, $\theta_{ei}$,$\theta_{eii}$) for the two tunnel kilns in [11] could be calculated as (0.74, 2.85, 0.35) and (0.68, 2.13, 0.47), respectively. The reason for low environmental performance of the current tunnel kiln compared to the tunnel kilns reported in [11] was the heat recovery from the tunnel kiln to the tunnel drier. Exergy destructed in the drier reduced the environmental performance indicators of the control volume composed of the tunnel kiln and the tunnel drier.

When the specific exergoenvironmental cost and specific sales income are shown in Figure 8 with a cyclic representation of sustainability check, it is seen that extra specific capital cost is needed to compensate the difference in the internal sustainability loop.

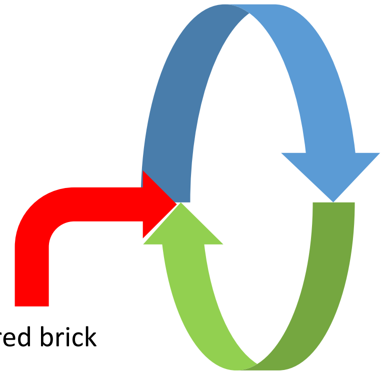


***Figure 8.*** *The sustainability loop*

## 5. CONCLUSIONS

The difference between the specific exergoenvironmental cost and the sales income in the sustainability loop should be compensated for a sustainable brick production. For this purpose, the following enhancements are suggested for maintaining sustainability:

a) Heat recovery from the kiln. The zero pressure on the kiln should be controlled sensitively to prevent the flue gas entrance to the dryer with the heat recovery. In this way, emissions cannot give harm to the metalwork in the dryer reducing the maintenance costs.
b) The ash content of the heat recovery causes the breaking of the electrical fan motors inside the dryer. To prevent the ash coming from the kiln to the dryer, heat exchanger can be installed in the heat recovery line.
c) Reusing the unburnt coal as admixed coal in the brick production will decrease the waste emissions.
d) With the production of value added face bricks in the control volume, the specific sales income will be more than the exergoenvironemtal cost.
e) Good maintenance of the equipment in the control volume, inreases the lifetime of the control volume which reduces the annual capital rate. This effect can be seen in the age of the studied control volume which is 46 years old.
f) To prevent the breaking of the refractory on the kiln cars, refractory including cordierite mineral should be used. This will reduce the exergoenvironmental cost by reducing the maintenance cost of the control volume.
g) With a SCADA control, the consumption of fuel can be reduced, which will reduce the exergoenvironmental cost. Also, a better control of the temperature of the dryer will prevent the damage of the fan motors installed inside the dryer.
h) Although the environmental damage of coal fuel is higher than that of natural gas, coal is preferred because of its lower price.
i) To reduce the rate of waste emissions, biomass fuel can be mixed to the coal. The ratio of biomass in the coal cannot be more than 5% for an even mixture of fuel and an even temperature distibution in the tunnel furnace.
j) As an effort to prevent the dust yielded in the coal crushing process, dust bags in the cyclon were used. Similarly, environmental damage preventive damage filters can be installed on the furnace chimney although the measured waste emission rates are lower than the regulation thresholds. The waste emission rate regulation threshould should be lowered in order to save our world from the dangers of the climate change.

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## CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

## NOMENCLATURE

$C$ : *cost (€)*
$\dot{C}$ : *cost rate (€/h)*
$\dot{C}A$ : *annual cost rate (€/h)*
$cf$ : *coefficient of exergoenvironmental impact*
$CRF$ : *cost rate factor*
$\dot{E}x$ : *exergy rate (kW)*
$f$ : *exergoenvironmental factor*
$i$ : *interest rate (%)*
$\dot{m}$ : *mass flow rate (kg/h)*
$PW$ : *present wort (€)*
$r$ : *inflation rate*
$R$ : *ratio of exergy loss rate to the annual investment*
$S$ : *salvage value (€)*
$\dot{S}$ : *salvage rate (€/h)*
$\dot{W}$ : *work rate or power (kW)*
$\dot{Z}$ : *capital cost rate (€/h)*

*Greek Letters*
$\theta$ : *damage factor*
$\varepsilon$ : *exergetic efficiency (%)*

*Indices*

$\alpha$ : *scaling exponential*
*CI* : *capital investment*
*CO* : *carbon monoxide*
$CO_2$ : *carbon dioxide*
*cv* : *control volume*
*d* : *destructed*
*ei* : *environmental impact*
*eii* : *enhancement in the environmental impact*
*elec* : *electricity*
*ex* : *exergoeconomic*
*exen* : *exergoenvironmental*
*env* : *environmental*
*in* : *inlet, input*
*k* : $k^{th}$ *component*
*l* : *lost*
*n* : *lifetime, nominal*
*NO* : *nitrogen monoxide*
$NO_2$ : *nitrogen dioxide*

*OM* : *operation and maintenance*
*out* : *output*
*PM2.5* : *dust*
*q* : *heat*
$SO_2$ : *sulphur dioxide*
*w* : *work*
**.** : *rate or quantity per unit time (over dot)*

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