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The Most Cost Effective Gas Cleaning Device in Steel Industry with Industrial Ecology Approach

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Abstract

Industrial growth and environmental damages, as two important indicators in sustainable development are followed by steel industry. This article leads industries to green industry. In this case, energy, material, capital consumption and environmental damages as sustainability patterns of environment have been investigated in three different dust collectors to select the most environmentally suitable dust collector for different furnace tonnages. In this way total cost in 3 mentioned dust collectors were calculated in four furnaces with capability of 1, 3, 6 and 12 tonnages. The results indicated that venturi scrubber dust collector for 3-ton and less capability furnaces was the most suitable option in terms of environmental sustainability and industrial ecology. But for the capacities beyond 3 tons, the usage of bag filters and electrostatic precipitator dust collectors were more suitable.

Keywords: Dust collector; Steel industry; Energy, Industrial ecology; Cost.

1. Introduction

Industrial ecology is a rapidly growing field that systematically examines local, regional and global materials and energy uses and flows in products, processes, industrial sectors and economies. It focuses on the potential role of industry in reducing environmental burdens throughout the product life cycle from the extraction of raw materials, to the production of goods, to the use of those goods and to the management of the resulting wastes. Industrial ecology is ecological in that it (1) places human activity -- industry in the very broadest sense -- in the larger context of the biophysical environment from which we obtain resources and into which we place our wastes, and (2) looks to the natural world for models of highly efficient use of resources, energy and byproducts [1)]. In 1991, the National Academy of Science's Colloquium on Industrial Ecology constituted a watershed in the development of industrial ecology as a field of study [2)]. Steel industry requires the most energy amount in comparison with other industries. Deterioration process of natural resources, fossil energies and also gas reserves have forced the scientists and researchers to take steps in order to reduce energy consumption (EC) [3)]. 20 to 25 percent of the steel cost in the United States is energy cost. Over the past 40 years energy consumption in electric arc furnaces in the world has dropped from 630 kWh to 300 kWh per tons of steel which 14% of this energy is related to exhaust gas control devices [4)].EC in each system, more or less, has environmental damages (EDs); therefore promoting energy consumption efficiency should have high priority in the industrial ecosystems design [5)]. For example, effects of electricity fuel cycles on employment, government revenues and global warming are considered in a paper by Krupnick and Burtraw. They assume that marginal damages are constant with very small changes in emissions;

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other things equal, existing plants, which generally emit higher quantities of pollutants per kWh produced, cause greater damages than new plants [6]. In the environmental impact assessment of the steel industries, the most impact on environment is related to air pollution resulting from electrical melting furnace [7]. Also, when hundreds of thousands dust collectors installed worldwide are considered, their impacts on global warming can be noticed which is due to the EC of the dust collectors [8]. The most important industrial dust collectors which are used to trap dusts of melting furnaces in steel industry are venturi scrubber (VS), electrostatic precipitator (ESP) and bag filter (BF) [9]. ESPs separate the particles and dusts from gas flow using electrostatic forces [10] due to their high total particle collection efficiency (99.9 %) [11].These devices draw the dusts and particles into the plates by producing a voltage difference and separate them from gas flow [12].Industrial applications of ESP are more in power plants, steel, gypsum and cement industries [13]. One of the impacts of ESP is production of ozone gas [14-16] and also damaging respiratory systems of human and plants [17]. VS dust collector is one of the most important wet collectors which works based on encounter of dust and water. The mechanism of VS can be described in this way that, first, water is entered into the convergent or throat of the venturi by water pump and then, the polluted air which contains gases, dusts and particles is also entered into the convergence part of the VS. Due to mixture of water and polluted air, dusts and gases are washed and on arriving the diverging section of the dust collector [18], they have been turned to water drops and directed to the waste water part through a conductor tube [19]. BF dust collectors are one of the main methods to prevent the discharge and release of dust in the atmosphere by using pulse jet method [20]. During the filtration, dusts are placed on the outer surface of fabric filter, which is caused by differential pressure of the suction fan system. Dusts and obstacles should be cleaned after being placed on the outer surface of the filter, regularly and periodically [21]. Considering the goals of industrial ecology based on reducing EC, capital and materials, and also decreasing the EDs, the need for researches to select an appropriate dust collector in steel industry (melting furnaces) seems to be necessary. Accordingly, annual consumption amount of energy and material, EDs due to these two parameters and also capital cost (considering the discount rate) are calculated for VS and ESP. It is worth mentioning that when EC is higher, the EDs are also more [22].In the case of low resistivity dust, conventional ESP results economically convenient with respect to fabric filter, especially when the gas flow rate increases [23].

2. Material and Methods

In this article, the consumption amount of energy, costs, EDs due to the EC, material, capital and total costs were determined in VS, BF and ESP connected to 1, 3, 6 and 12-ton electrical furnaces of a steel industry in Iran in 2011, by the use of computational methods [24]. In order to determine the capital cost, it was necessary to compute the related costs such as expenditure of purchase, installation and operation of each dust collector. Then, based on the life time of dust collectors, depreciation costs of dust collectors were calculated. Finally, annual interest of purchase cost and device installation were calculated using the discount rate and interest rate, in order to obtain capital total cost of dust collectors.

To determine the energy costs in dust collectors, EC amount was determined based on the devices that use electricity power and were connected to dust collectors, such as fans, transformers, compressor and pumps. Then, using the real price of electricity and annual consumption of dust collectors, annual EC cost was calculated.

To calculate the cost of consumed material based on dust collector type, firstly annual amount of consumed materials such as fabric filters, cages (in BF) and annual water consumption (In VS) were calculated and multiplied into the real price of consumed material.

In order to determine EDs caused by EC of dust collectors, energy rate and cost of EDs were calculated. Finally, the optimal dust collector could be compared and chosen by summarizing the costs of capital, consumed material, EDs and energy in dust collector working life time.

2.1. Calculation of annual consumption of energy, material, capital and Environmental Damages for BF, ESPs and VS

The annual EC in a centrifugal fan connected to ESP, BF and VS was determined in Eq. (1), after rearranging to SI unit [25].

$$FP = 0.00026(Q)(\Delta P)(\theta) \qquad \text{Eq. (1)}$$

Where, FP is fan power requirement ($kw.yr^{-1}$), θ is annual operating time ($hr.yr^{-1}$), Q is the capacity ($m^3.min^{-1}$) [26] and ΔP is System pressure drop (Pa) [7]. Normally, the amount of pressure drop in BFs was approximately 4 to 6 inches of water gage and the amount of pressure drop in VS was estimated in Eq. (2) after rearranging to SI unit.

$$\Delta P = 2.450827 \times V^2 \times \rho_g \times A^{0.133} \times (\frac{L}{G})^{0.78} \qquad \text{Eq. (2)}$$

Where, ρ_g is saturated gas stream density in Pa, V is throat velocity in meter per second (m/s), L/G is liquid to gas ratio in gallons per m^3 (gal/m^3) and A defines the cross-sectional area of the throat in square meter (m^2).

In Eq. (2) which is known as Hesketh equation, the amount of liquid to gas was considered about 3 to 10 gallons per 1000 cubic feet [7].The annual EC amount caused by compressors in BFs was determined in Eq. (3).

$$\omega = \frac{1}{\eta} \times \frac{1}{\gamma - 1} P_1 Q_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{(\gamma-1)}{\gamma}} - 1 \right] \quad \text{Eq. (3)}$$

Where, ω is real power of compressor, ηis efficiency of the compressor (0.5), γ is specific heat of air (1.4), P_1 is initial pressure (KPa), P_2 is final pressure (KPa), Q_1 is volumetric flow of compressor ($m^3.s^{-1}$). The amount of compressed air to shake the filters was 0.5 % of fan capacity connected to dust collector, also the final pressure caused by compressor to shake the filters was about 792 (KPa)(100 psig) and initial pressure of one atmosphere is 101.3. The volumetric flow of the compressor is obtained by Eq. (4).

$$Q_1 = Q_2 \times \frac{T_1}{T_2} \times 0.005 \quad \text{Eq. (4)}$$

Where, Q_1 is volumetric flow of the compressor (m^3), Q_2 is volumetric flow of fan ($m^3.s^{-1}$), T_1 is the temperature of environment (Kelvin), T_2 is the inlet temperature of BF (Kelvin) [27].

The annual EC of transformers in EPS is determined in Eq. (5) after rearranging:

$$OP = 0.0208 \times A\theta \quad \text{Eq. (5)}$$

where, OP is ESP operating power ($kw.hr^1$), A is ESP plate area (m^2), and θ is annual operating time ($hr.yr^{-1}$).

In order to determine the area of the plates for calculating the EC of transformers and shakers in ESPs, the simplest form of the equation is given below as Eq. (6) [25].

$$\eta = 1 - e^{\left(\frac{-\omega A}{Q}\right)} \quad \text{Eq. (6)}$$

Where, η is collection efficiency of the precipitator, A is the effective collecting plate area of the precipitator (m^2), Q is Gas flow through the precipitator, ($m^3.s^{-1}$), e is base of natural logarithm, and ω is migration velocity ($cm.s^{-1}$)

To calculate annual EC due to electromotor of the pump in VS, first, the pressure drop of the pump which was a function of VS length was determined in Eq. (7), and then, the energy amount due to electromotor of the pump was calculated using Eq. (8):

$$A = \frac{Q}{V} \quad \text{Eq. (7)}$$

, where, Q is capacity rate of gas ($m^3.s^{-1}$), V is the fluid velocity in the throat ($m.s^{-1}$) and A is cross section of VS throat (m^3).

$$HP_{pump} = \frac{6.1985 \times 10^{-4} \times \Delta P_{pump} \times \frac{L}{G} \times Q \times \gamma}{\eta_{pump}} \quad \text{Eq. (8)}$$

, where, HP_{pump} is pump brake (KW), η_{pump} is efficiency of the fan (usually equal to 0.7), ΔP is pressure of the pump (m_{H2o}), L/G is the ratio (gallons per m^3), Q is the flow rate at inlet (cubic meter per minute) and γ is gravity of the scrubbing liquid (1.12).

In order to determine the annual material consumption (water) in the dust collector, equation 15 was used and in order to achieve the annual water consumption in VS, the following procedure was used:

1) Converting the volumetric flow of polluted gas into volumetric flow.
In order to convert the volumetric flow of polluted gas into volumetric flow, Eq. (9) was used:

$$Q_{scfm} = Q_{acfm} \times \frac{T_s + 460}{T_a + 460} \quad \text{Eq. (9)}$$

, where, Q_{scfm} is standard volumetric flow, Q_{acfm} is real volumetric flow, T_s is temperature at standard condition, and T_a is real temperature.
2) Mass flow of water vapor and dry air were calculated using Eqs. (10) and (11):

$$m_{wv(in)} = Q_{scfm} \times 0.25 \times \frac{MW_{wv}}{V_{mol}} \quad \text{Eq. (10)}$$

$$m_{a(in)} = Q_{scfm} \times 0.75 \times \frac{MW_a}{V_{mol}} \quad \text{Eq. (11)}$$

, where, $m_{wv(in)}$ is mass flow rate ($kg.min^{-1}$), $ma_{(in)}$ is mass flow of dry air ($kg.min^{-1}$), Q is standard volumetric flow of gas ($m^3.min^{-1}$) , MW_{wv} is Molecular weight of water vapor [(19)] , MW_a is molecular weight of the air [28] and V_{mol} is volume of one mole of air (0.062 m^3. Kg moles).
3) Determination of humidity amount: The inlet humidity was determined in Eq. (12):

$$\omega_{(in)} = \frac{m_{wv(in)}}{m_{a(in)}} \quad \text{Eq. (12)}$$

, where, $\omega_{(in)}$ is amount of inlet humidity.
4) Real relative humidity and the real temperature of the gas and new parameters were determined referring to psychometric chart. In the chart, the intersection point of two parameters of inlet humidity and temperature of the gas will be determined.
5) The mass of outlet water vapor was determined in Eq. (13):

$$m_{wv(out)} = m_{a(in)} \times \omega_a \quad \text{Eq. (13)}$$

, where, ω_a is real relative humidity, $m_{wv(out)}$ is the mass flow of outlet water vapor , and $m_{a\,(in)}$ is mass flow of inlet dry air.

6) The mass of water evaporated through the scrubber is:

$$m_{wv(evap)} = m_{wv(out)} - m_{wv(in)} \quad \text{Eq. (14)}$$

, where, $m_{wv(evap)}$ is mass flow of evaporated water (kg.min^{-1}) , $m_{wv(in)}$ is mass flow of inlet water (kg.min^{-1}) and $m_{wy(out)}$ is mass flow of outlet water vapor (kg.min^{-1}).
7) The volume flow rate of water is given by Eq. (15):

$$Q_{wv(evap)} = \frac{m_{wv(evap)}}{\rho} \quad \text{Eq. (15)}$$

, where, $Q_{wv(evap)}$ is capacity of consumed water, $m_{wv(evap)}$ is mass flow of evaporated water (kg.min^{-1}), and ρ is water density (kg.m^{-3}).

Fabric filter and bag cages were used in FB dust collector. The filter fabric is decayed every two years and cloth of storage cages is decayed every five years. The amount of used fabric can be determined through the velocity limit of the fabric surface. For example, the velocity limit for iron oxide dust was approximately 7 feet per minute and was determined in Eq. (16):

$$A = \frac{Q}{V} \quad \text{Eq. (16)}$$

, where, A is the filtration surface (m^2), Q is volumetric flow of gas (m^3.s^{-1}) and V is the velocity on the Filter Surface (m.s^{-1}).

The bags were typically about 16 cm in diameter and their length was about 3.5 m. it means that for each filter, about 1.75 m^2 of fabric were used. By dividing the total surface of the filter into 1.75 m^2, the amounts of filters and relevant cages were determined for each BF system.

2 .2. Calculation of capital, energy, materials and Environmental Damages costs in BF, VS and ESPs

Capital costs in a dust collector system consist of original purchase, installation, depreciation and cost of capital annual benefit [28]. Minimum cost of purchase in VS dust collectors was approximately 0.83 US $ for each cubic foot per minute and installation cost was 0.56 % of the purchase cost. The minimum purchase cost in BF is approximately 1US $ for each cubic foot per minute and the installation cost was 0.67 % of the purchase cost, While the minimum purchase cost in ESPs was approximately 1.25 US $ for each cubic foot per minute and the installation cost is 0.67 % of the purchase cost [29].

In order to determine the cost of annual depreciation in dust collector systems, first, the discount rate was equal to difference of highest bank interest and average inflation rate, and then the coefficient capital recovery factor was calculated in Eq. (17). The annual depreciation cost in dust collector was achieved using Eq. (18), where the coefficient was multiplied into in to initial capital cost.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \text{Eq. (17)}$$

$$CRC = C \times CRF \quad \text{Eq. (18)}$$

Where CRF is capital recovery factor, i is discount rate, n is system lifetime, CRC is capital recovery cost and C is capital cost. In order to obtain annual benefit cost of capital, it was required to multiply the total initial cost into discount rate (Eq. (19)):

$$CB = i \times TC \quad \text{Eq. (19)}$$

, where CB is annual benefit cost of capital, i is discount rate and TC is total initial capital cost.
The electricity consumption cost should be multiplied into the annual EC amount (which has been mentioned in Eqs. (1, 3, 5) and (8). In Iran, industrial electricity consumption cost is 0.03 US $ per kilowatt. This number was multiplied into annual EC which has been obtained by Eqs. (1, 3, 5) and 8. To determine consumed materials (water) in VS, the industrial water consumption cost which is 0.33 US $ per m^3 in Iran, had to be multiplied into annual water consumption.
Approximate cost of each BF by 16 cm diameter and 3.5 m length is about 12.5 US $ and approximate cost of the cage is 20.8 US $.

Considering the issue, that for producing one KWH electricity, 0.0108 US $ has been determined; therefore, to determine ED due to usage of mentioned dust collectors, the electricity consumption amount caused by each dust collector was multiplied into 0.0108 US $ [21].

3. Results & Discussion

The results of the calculations of annual total capital costs containing purchase, installation, commissioning, annual benefit in ESPs, BF and VS connected to the 1,3, 6 and 12 ton furnaces are shown in Table 1, which reveals that ESPs cost is 1.6 times more than VS and 1.2 times more than BF. The results obtained from calculations of consumption and annual energy costs in ESP, VS and BF are expressed in Tables 2 and 3 which represent that by increasing the tonnage of the furnaces, the amount of annual energy would be increased linearly in VS, BF and ESP. Also by doubling the tonnages of the furnaces, EC and annual energy cost would be doubled. In addition, the amount was the lowest in ESP and then in VS and BF. The amount of annual energy consumption in BF was four times greater than ESP and the amount in VS was five times greater than ESP.

And also, the amount of material consumption such as fabric filter and cages are shown in Table 4 which indicates that by doubling the capacity of the furnaces, the amount of fabric Filters and cages will be doubled.

Table 1. Annual capital cost in VS, ESP and BF (US $).

Dust collector type	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
VS	3448.2	10344.7	20689.5	41379
ESP	5537	16611.2	33222.5	66445
Bag Filter	4614.2	13842.5	27685.3	55370.8

Table 2. EC amount in VS, ESP and BF (KWH).

Dust collector type	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
VS	16410	44530	110230	225424
ESP	3471	10415	20864	41729
Bag Filter	12848	43800	87600	175200

Table 3. Annual EC costs in VS, ESP and BF (US $).

Dust collector type	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
VS	547	1483.3	3674.3	7514
ESP	3471	347.16	695.46	1390.96
Bag Filter	428.2	1460	2920	5840

Table 4. Amount of fabric filter consumption (every 2 years) and Cage (Every 5 years).

Consumed material	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
Bag (number)	19	57	114	228
Cage (number)	19	57	114	228

Table 5. Annual water consumption amount in VS (Cubic Meter).

Consumed material	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
Water (cubic meter)	41	123	246	492

Table 5 presents water consumption amount in VS. When the capacity of the furnaces is doubled, water consumption amount is also doubled.

Table 6 presents the cost of materials consumption such as Bag Filter, cages and evaporated water in VS and BF. The table indicates that by doubling the capacity of the furnaces, the amount of consumed materials would be also doubled.

Table 7 presents the amount of EDs due to EC caused by operations of Bag Filter, VS and ESPs. It indicates

Table 6. Annual cost of fabric filter consumption, cage and water in BF and VS (US $).

Dust collector type		1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
Bag Filter	BF cost	118.75	356.2	712.5	1425
	Cage cost	79.1	237.5	475	950
	Total cost	197.9	593.75	1187.5	2375
VS	Water consumption cost	13.6	41	82	164

Table 7. ED cost caused by EC in dust collectors (US $).

Dust collector type	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
VS	177.7	482.4	1194	2442
ESP	37.5	112.8	226	452
Bag Filter	138.7	474.5	949	1898

Table 8. Annual cost of EDs, capital, energy and material in VS, ESP and BF (US $).

Dust collector type	1 ton furnace	3 ton furnace	6 ton furnace	12 ton furnace
VS	4186.7	12352.5	25640	51499
ESP	5656.56	17071.3	34144	68288.1
Bag Filter	5379.5	16371	32742	65484

that by increasing the tonnages of furnaces, the amount of ED would be increased linearly in dust collectors and by doubling the tonnages, the ED would be doubled and annual ED costs of BF were four times greater than ESP and the amount was five times greater in VS.

The table indicates that by doubling the capacity of the furnaces, the amount of EDs caused by BF and ESPs would be doubled.

Table 8 presents annual cost of EDs, capital, energy and material in VS, ESP and BF during the first year and indicates that by doubling the tonnages of furnaces, the ED amount would be doubled and the amount of ED in BF was four times greater than ESP and the amount in VS was the lowest amount and while the tonnages increase, the cost difference would also increase.

Table 7 presents the amount of EDs due to EC caused by operations of Bag Filter, VS and ESPs. It indicates that by increasing the tonnages of furnaces, the amount of ED would be increased linearly in dust collectors and by doubling the tonnages, the ED would be doubled and annual ED costs of BF were four times greater than ESP and the amount was five times greater in VS.

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As it can be seen in Figs. 1, 2, 3 and 4, the least amount of total cost belonged to VS and then respectively to ESP and BF at the end of the second year.

The total cost was the same in VS and ESP at the end of the third year and then, belonged to BF.

Since the fifth year, the least amount of total cost belonged to ESP and then respectively to VS and BF. Overtime, although there was no difference between VS and BF, there was a significant difference between these two dust collectors and ESP. This difference was 1.6 times greater at the end of the tenth year and 2.5 times greater at the end of the twentieth year. The amount of total cost can be observed in Figs. 1, 2, 3 and 4 and it has been cleared that since the fifth year, the total cost difference including capital, energy and material consumption and environmental damages increased between BF and VS

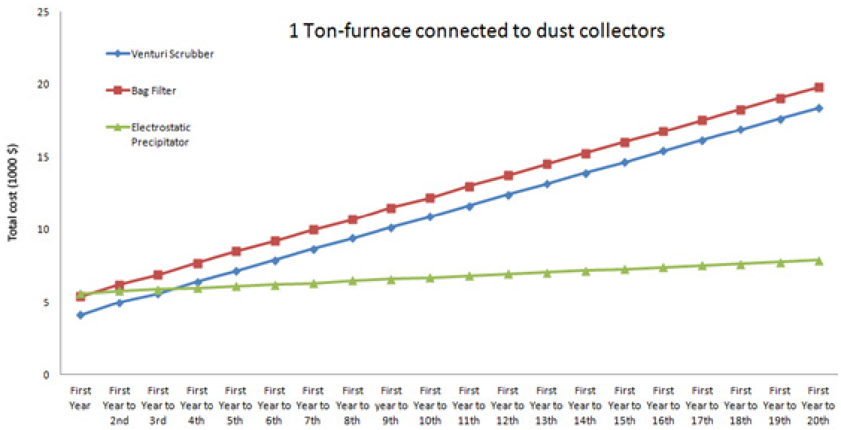

Fig. 1. Total cost for VS, BF and ESP in 1 ton furnace during 20 years operation.

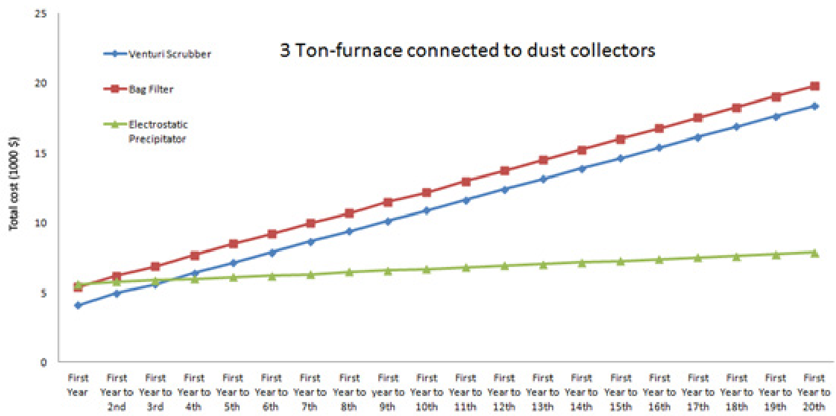

Fig. 2. Total cost for VS, BF and ESP in 3 ton furnace during 20 years operation.

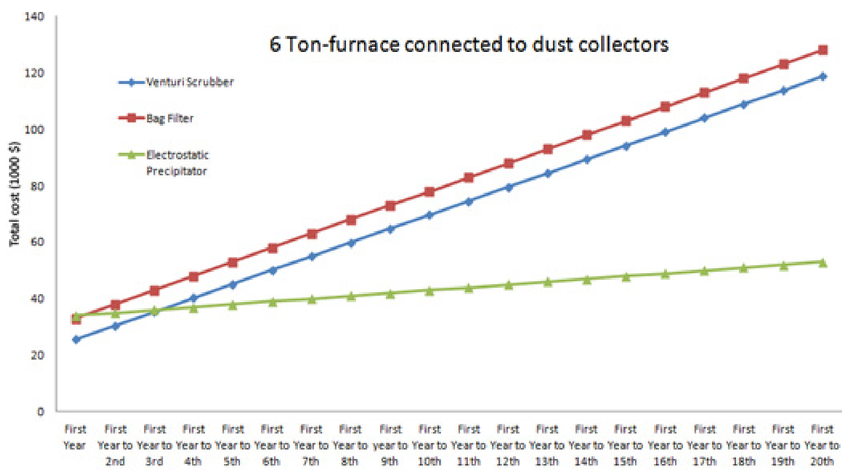

Fig. 3.Total cost for VS, BF and ESP in 6 ton furnace during 20 years operation.

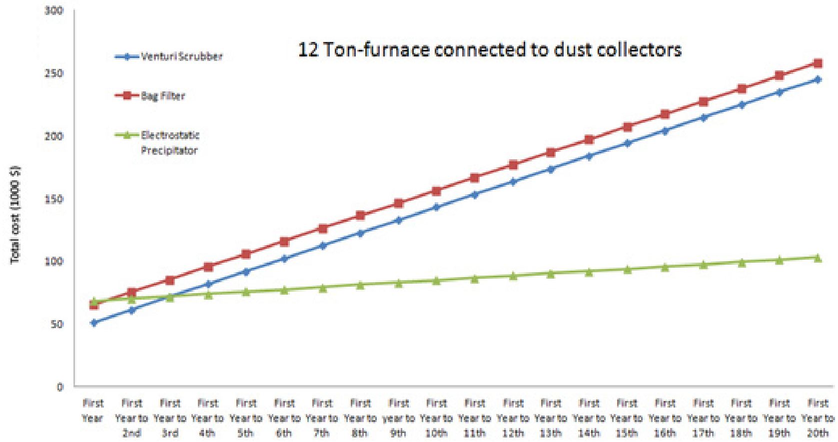

Fig. 4. Total cost for VS, BF and ESP in 12 ton furnace during 20 years operation.

with ESP. Although, there was a few difference between BF and VS overtime, since the eleventh year the total cost increased in VS.

On one hand, the usage of VS and BF produce various gases including nitrogen dioxide, sulfur dioxide, carbon monoxide, organic compounds and particles from power plants due to consumption of high energy which causes harmful impacts on humans, plants and environment and on the other hand, the usage of ESP (despite the low EC) due to overvoltage, produces troposphere ozone [28].

4. Conclusions

According to the results of calculations and aims of industrial ecology, to reduce EC, capital, material and EDs, the best dust collector for a 20 year -period was ESP because the amount of total costs in BF and VS were 2.5 times greater than the ESP at the end of the 20th year.

The best option for a five- year period was BF. Although costs were slightly more in BF and VS and system costs of VS and ESP were the same for a five -year period and are more in BF, but because of producing the ozone gas, usage of VS seems reasonable and although the EC, capital, material and EDs of VS were slightly less than BFs, but because of maintenance problems caused by pump clogging, pipes and sprinkler and subsequently decreasing de-dusting and stopping the project, using VS dust collector, is not recommended. The best option for a 10 -year period depends on the distance between the steel industry and the cities. If the steel industry is located near the rural and urban areas, the best dust collector will be BF. Because although the costs are slightly more in BF and VS than ESP but ESP can cause environmental damages by producing ozone gas. If the steel industry works more than five years and is located far from rural and urban areas, usage of ESP will be more appropriate in terms of industrial ecology because the ozone gas produced by ESP is diluted in far distances.

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