ENERGY SAVINGS AND EMISSION REDUCTIONS IN INDUSTRIAL BOILERS

by

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Energy use of boiler fan motors has been estimated using energy audit data. Energy savings using variable speed drive by modulating fan speed has been estimated as well. Bill savings and associated emission reductions using variable speed drive have been estimated and presented. It has been found that 139,412, 268,866, 159,328, and 99,580 MWh electrical energy can be saved for 40, 60, 80, and 100% motor loadings, respectively for 60% speed reduction. Corresponding bill savings for the aforementioned energy savings have been found to be 7,318.335, 14,113.933, 8,363.812, and US 135,911.944 for 40, 60, 80, and 100% motor loadings, respectively, for 60% speed reduction. Along with energy savings, 69,770.744, 134,558.329, 79,738.065, and 49,836.603 kg of CO_2 emission can be avoided for the associated energy savings as a result of energy savings using variable speed drive for 40, 60, 80, and 100% motor loadings. Moreover, 32,503.558 GJ of fossil fuel can be saved for the flue gas temperature reduction as a result of reducing fan motor speed reduction. Flue gas energy savings for oxygen trim system has been estimated and found to be 549,310,130 GJ for 16.9% of excess air reduction with payback period less than a day.

Key words: *boiler energy savings, variable speed drive, emission reductions*

Introduction

Steam systems are a part of almost every major industrial process today. Thirty-seven percent of the fossil fuel burned in US industry is burned to produce steam. This steam, in turn, is used to heat processes, to concentrate and distill liquids, or is used directly as a feedstock. All of the major industrial energy users devote significant proportions of their fossil fuel consumption to steam production: food processing (57%), pulp and paper (81%), chemicals (42%), petroleum refining (23%), and primary metals (10%). Since industrial systems are very diverse, but often have major steam systems in common, it makes a useful target for energy efficiency measures [1].

Nearly 45% of global electricity generation is derived from coal while natural gas and nuclear energy makes up about 20% and 15%, respectively, of the world's generated electricity [2]. Since these energy sources generally uses a boiler-steam turbine system to convert its chemical potential energy for electricity generation, one can only imagine the

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possible savings derivable from improving the efficiency of a steam boiler by just a small fraction. Most heating systems, although not all, employ boilers to produce hot water or steam. Boiler efficiency therefore has an important influence on heating-related energy savings. The energy savings that can be achieved by improving overall boiler efficiency can be substantial. Essentially a boiler is a device in which a fossil fuel is burnt and the heat produced is transferred to water. Heat can be lost from boilers by a variety of methods, including flue gas losses, radiation losses and, in the case of steam boilers, blow-down losses [3-6]. To optimize the operation of a boiler plant, it is necessary to identify where energy wastage is likely to occur [7-10]. A significant amount of energy is lost through flue gases as all the heat produced by the burning fuel can not be transferred to water or steam in the boiler.

The efficiency of boiler is a measure of the ability of it to generate the steam demand from a given fuel supply. A boiler should always be supplied with more combustion air than is theoretically required, in order to ensure complete combustion and safe operation. If the air rate is too low, there will be a rapid build up of carbon monoxide in the flue gas and, in extreme cases, smoke will be produced (*i. e.* unburned carbon particles). At the same time, boiler efficiency is very dependent on the excess air rate. Excess air should be kept at the lowest practical level to reduce the quantity of unneeded air that is heated and exhausted at the stack temperature. To improve boiler efficiency, the logical approach is to identify the losses, determine their relative magnitude and then to concentrate first on reducing the losses that have the greatest impact on boiler efficiency. As the temperature of the flue gas leaving a boiler typically ranges from 150-250 °C, about 10-30% of the heat energy is lost through it [11]. Since most of the heat losses from the boiler appears as heat in the flue gas, the recovery of this heat can result in substantial energy savings [12]. This indicates that there is huge savings potentials of a boiler energy savings by minimizing its losses. Figure 1. shows boiler efficiency in dependence with the flue gas temperature reduction.

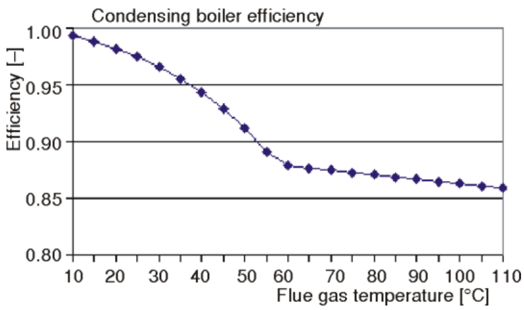

Figure 1. Boiler efficiency *vs.* flue gas temperature [8]

By introducing variable speed to the driven load, it is possible to optimize the efficiency of the entire system, and it is in this area that the greatest efficiency gains are possible [13]. A variable speed drive (VSD) was used on the fan motor to change excess air ratio as well. In the literatures, there are few works about the details estimation of boiler energy and environmental analysis. Considering that a boiler electrical energy use, savings, associated bill savings and avoided emission have been estimated and presented in this paper. It is expected that the estimation will be very useful for industry, policy makes, energy users, and researchers.

Stack gas heat losses

The biggest energy losses in a conventional oil fired boiler occur through the chimney. The size of the heat loss depends on the temperature and volume of the gas leaving the boiler; therefore, reducing either of these will reduce the heat loss. Some stack gas heat losses are unavoidable, but to eliminate these losses, the stack gas temperature would have to be reduced to the air temperature around the boiler.

The three basic strategies for minimising stack gas losses are:

(1) minimising excess air,
(2) keeping heat transfer surface clean, and
(3) adding flue gas heat recovery equipment where justified.

It may be mentioned that with reduced excess air, stack gas volume is also reduced. The temperature of the gas also decreases because gas velocities are reduced, allowing gas to spend more time in the boiler where the heat can be absorbed. Most conventional boilers are 75-90% efficient, so ways should be sought to reduce the resulting 10-25% waste energy.

Energy losses arise principally in four categories in the boilers:

- heat carried out of the stack by dry flue gasses excluding water vapour (dry flue gas loss),
- heat carried out of the stack by hot water vapour, including both sensible and latent heat,
- unburned fuel and products of incomplete combustion, including solid combustibles in ash and carbon monoxide in flue gas, heat lost from the boiler structure through the insulation (radiation and convection losses from the outside surface), and
- heat carried away with boiler blow-down.

As a rule of thumb, a boiler efficiency can be increased 1% for every 15% reduction in excess air; or 1.3% reduction in oxygen. In a computer-based system, new control logic can be added for a fraction of what it would cost to add the same control on an older system. Modern, multiple burner control, coupled with excess air trim control using control logic can result in fuel savings of 3% [14].

Excess air control

A boiler should always be supplied with more combustion air than theoretically required in order to ensure complete combustion and safe operation. At the same time, boiler efficiency is very dependent on the excess air rate. Therefore, the excess air should be optimised to increase the system efficiency. In order to complete combustion, the desired air flow of the fan is determined by the employment of one of the following:

(1) inlet damper control,
(2) inlet vane control, and
(3) variable speed control.

In this case, VSD is used, which is a way of the most efficient control method. It provides only the power necessary to overcome system resistance at a given condition. Currently, variable speed drives are commonly used in modern industrial and commercial boilers. The modern boiler systems are designed, equipped, and practiced with the described method at present time. It is particularly effective when operating conditions call for frequent low load periods. Table 1 shows the energy savings associated with the speed reductions as a result of using VSD.

Table 1 Potential savings from VSD [13]

Average speed reduction [%]	Potential energy savings [%]
40	73
60	89

Qureshi *et al.* [14] reviewed the VSD in refrigeration application to reduce energy uses.

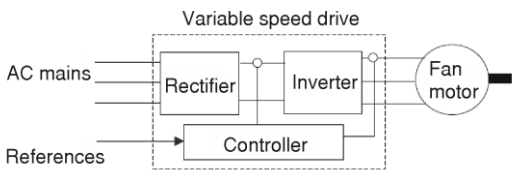

Figure 2. The block diagram of the variable speed drive system [4, 5]

Variable frequency drives (VFD) are routinely used to vary a pump and fan speed in heating, ventilating and air conditioning of buildings as can be seen in fig. 2.

With mechanical cam control and with basic electronic fuel/air ratio control processor sacrifice combustion efficiency at low fire to achieve an improvement in burner turndown. Some air dampers leak and even air flow is fully closed can be significant. In effect, processors can reduce the fuel valve setting but cannot reduce the air to match. Combustion efficiency can be improved at low fire if the fan speed is reduced. The fan motor speed control is an easy to add option on some electronic controls. By adding fan motor speed control, burner turndown can be increased without compromising efficiency, and additional fuel savings can be achieved. The benefit of variable speed drive by using an inverter to slow down an AC electric motor causes electrical energy saving. For example, when a fan motor is slowed to 25 Hz, *i. e.* to half speed, an 80% electrical energy savings is achieved.

By adding a driver to the system, and controlling the fan motor speed, electrical energy is saved and by restricted excess air rate, stack losses are minimised. Hence, not only will boiler efficiency be increased, but operating the motor with variable speed will also save electrical energy. Oxygen trim saves fuel, reduces emissions, and extends the life of the boiler plant [11, 15]. Electric motors are over 90% efficient when running at their rated loads. However, they are very inefficient at load-following, or running at part loads. Conventional electric motors typically use 60% to 80% of their rated input energy, even when running at less than 50% load. Motors operated lower than 50% of rated load, because they were chosen in big capacity, performing inefficiently, and due to the reactive current increase, power factors are also decreased. These kinds of motors do not use the energy efficiently because they have been chosen in for large motor power, not according to the needs. These motors should be replaced with new suitable capacities of motors, and when purchasing new motors, energy saving motors should be preferred [16].

The cost of an adjustable speed motor can vary quite a bit depending upon the particular features and durability. Per-horsepower (0.746 kW) costs decrease significantly with size, from an average of about $640 per horsepower for a 20 horsepower application to about $150 per horsepower for a 20.000-horsepower application [17, 18]. It was mentioned in the reference that a 10 HP, 460 volt drive with line reactor will cost about $1300. Installation time, materials and start-up will cost $500 or more [19]. First costs for variable-frequency drives are relatively expensive. Installed drives range from about $3.000 for a 5 horsepower motor to almost $45.000 for a custom-engineered 300 horsepower motor, and more for larger versions [19, 20].

Methodology

Data collection

Malaysian Energy Centre (MEC) conducted energy audit for 48 industrial facilities for about 2 years starting from 2002-2004 [21]. It was a detailed energy audit. Summary of

Table 2. Type and number of audited industry

Industry	No.
Food	10
Wood	7
Ceramic	6
Cement	3
Glass	3
Rubber	9
Pulp and paper	6
Iron and steel	4
Total	48

type and number of industry visited is shown in tab. 2. Number of fan motor and their corresponding power, motor loadings, and usage hours are presented in tabs. 3 and 4. These are the data needed for boiler fan motor energy analysis.

Table 3. Boiler operating time with its loading

Boiler loading	Operating hours/year
100%	720
80%	1440
60%	3240
40%	2520

Table 4. input data for motor energy analysis

Serial No.	Motor power [kW]	Quantity	Motor power [kW] for 40% speed reduction	Motor power [kW] for 60% speed reduction
1	11	50	8	10
2	15	66	11	13
3	19	21	14	17
4	22	15	16	20
5	30	17	22	27
6	37	9	27	33
7	45	5	33	40
8	56	3	41	50

Mathematical formulations to estimate energy use and savings using VSD

Anual energy used (*AEU*) by motor fan can be estimated using [22, 23]:

$$AEU = n \cdot P \cdot L \cdot hr \tag{1}$$

where *hr* are the annual operating hours, *L* – the load factor, *P* [kW] – the motor power and, *n* – the number of motors.

There are many ways to estimate the energy savings associated with the use of VSD for industrial motors for various applications. This paper employed the methods found in [12]. Energy use of fans and pumps varies according to the speed raised to the third power, so small changes in speed can result in huge changes in energy use. A motor energy savings (*ES*) using VSD can be estimated as:

$$ES_{\mathrm{VSD}} = n \cdot P \cdot H_{\mathrm{avg\_usage}} \cdot S_{\mathrm{SR}} \tag{2}$$

where $H_{\mathrm{ave\_usage}}$ is the average usage hours and S_{SR} is the speed reduction.

Table 1 shows the potential energy savings associated with the speed reduction using VSD for industrial motors [24]. These data have been used to estimate motor energy savings using VSD. Annual bill savings associated with the above energy savings can be calculated as:

$$\text{Savings} = AES \cdot c \tag{3}$$

where c is the cost of electricity (US$ 0.064 per kWh).

Estimation of fuel savings associated with boiler fan speed reduction

By adding fan motor speed control, burner turndown can be increased without compromising efficiency, and additional fuel savings can be achieved. By adding a driver to the system, and controlling the fan motor speed, electrical energy is saved and by restricted excess air rate, stack losses are minimised. Based on methodology explained by [24-26] stack gas loss (L_{stack}) was estimated. Concentration of O_2 and stack gas temperature with and without VSD were taken from Ozdemir [15] as well. Other necessary input data were also taken from this reference.

Digital control of excess air

The oxygen trim control system will correct the airflow so that the combustion efficiency remains as high as possible. Oxygen trim systems can improve the efficiency of a boiler by 1-2% [15]. For best excess air control, a digital monitoring control system, often called an "O_2 trim" system, can be installed on a boiler. An O_2 trim system consists of an exhaust-gas monitoring probe that communicates with the combustion air inlet damper via a central digital controller. Based on the O_2 level detected in the exhaust gas, the combustion air damper automatically adjusts to achieve a user-defined excess air set-point. To optimize combustion efficiency over a boiler's firing range, the O_2 set-point should be set to 1.7%, which corresponds to 10% excess air which provide highest combustion efficiency [27]. Rather than be linked by a jackshaft as in single-point positioning, the fuel valve and combustion air damper are controlled independently in O_2 trim control. Figure 3 displays the arrangement of a boiler O_2 trim system.

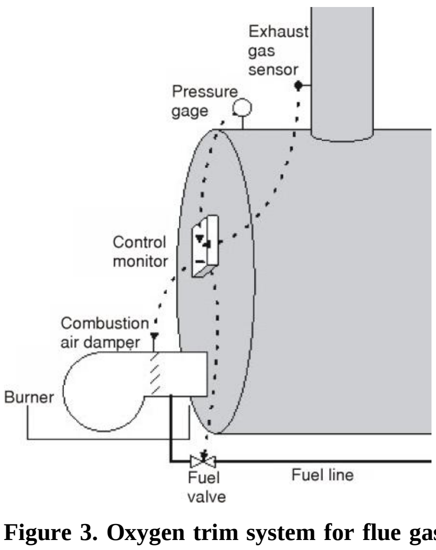

Figure 3. Oxygen trim system for flue gas recovery [24]

Determining combustion efficiency

The minimum amount of air required for complete combustion is called the "stoichiometric" air. As an example, the equation for the stoichiometric combustion of natural gas (comprised mostly of methane, CH_4) with atmospheric air is:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \tag{4}$$

The ratio of the mass of air required to completely combust a given mass of fuel is called the stoichiometric air/fuel ratio, AF_s. For natural gas, AF_s is about 17.2 kg-air/kg-ng. The quantity of air supplied in excess of stoichiometric air is called excess air, *EA*. The combustion temperature, T_c, can be calculated from an energy balance on the combustion chamber, where the chemical energy released during combustion is converted in sensible energy gain of the gasses. The energy balance reduces to the terms of inlet combustion air temperature, T_a, fuel lower heating value, *LHV*, excess air, stoichiometric air fuel ratio, and combustion gas specific heat, C_{pg} [24]:

$$T_C = T_a + \frac{LHV}{[1+(1+EA)AF_s]C_{pg}} \tag{5}$$

Combustion efficiency, η, is the ratio of energy transferred to boiler steam/water to the total fuel energy supplied. The energy transferred to steam/water is the energy loss of combustion gas as it travels through the boiler. On a per unit basis, eq. (5) can be written as an enthalpy difference in terms of combustion temperature and exhaust temperature, T_{ex}. The total fuel energy supplied on a per unit basis is the fuel's higher heating value (*HHV*). Equation (5) calculates combustion efficiency in terms of easily measured values:

$$\eta = \frac{(1+EA)AF_s C_{pg}(T_C - T_{ex})}{HHV} \tag{6}$$

Amount of fuel that can be saved by trimming excess air can be expressed as:

$$FS = FC \cdot S_{EAR} \tag{7}$$

where *FS* [GJ] is the fuel savings, *FC* [GJ]– the fuel consumption, S_{EAR} [%]– the fuel savings due to excess air reduction.

Table 5 presents the properties of natural gas used in flue gas energy analysis.

Table 5. Properties of natural gas [24]

LHV [MJkg^{-1}]	50
HHV [MJkg^{-1}]	55.55
C_{pg} [kJK^{-1}]	2.254
Price of natural gas [US$/GJ]	2
Cost of oxygen trim [US$]	32,000

Table 6. Incremental price for VSD [13]

Motor power [kW]	Incremental price [US$]
11	4176
15	5316
19	6123
22	6853
30	8656
37	10,387
45	12,117
52	14,321

Estimation of the payback period

A simple payback period for different energy savings strategies can be calculated using formulations presented in [9, 12, 23]. Table 6 presents additional cost of variable speed drive to modulate the speed of boiler fan motors so that energy can be saved.

Estimation of emission reduction

The energy savings is likely to reduce the electricity generation from power plants. As a consequence, the reduction of CO_2 and other emissions from the fuels used by the power sector can be estimated. The amount of emission that can be reduced associated with the energy savings can be estimated using the following equation [28]:

$$ER = AES \cdot EF \tag{8}$$

where *ER* [kg] is the emission reduction, and EF [kgkW^{-1}h^{-1}] – the emission factor.

Emission factor for per unit energy has been shown in tab. 7. and has been used to estimate the amount of emission that can be reduced.

Table 7. Emission factors of fossil fuels for electricity generation [25]

Fuels	Emission factor [kgkW^{-1}h^{-1}]			
	CO_2	SO_2	NO_x	CO
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Gas	0.53	0.0005	0.0009	0.0005
Hydro	0.00	0.000	0.0000	0.0000
Others	0.00	0.000	0.0000	0.0000

Results and discussions

Using eq. (1) and input data from tabs. 2 and 3, energy use by boiler fan motor for different capacities and percentage of loadings has been estimated and presented in fig. 4. Based on this figure it has been observed that more energy used by boiler fan motors for 60% loading followed by 40% as motors are engaged in operation for longer time compared to 80% and 100% loadings. It was also found that highest amount of energy used by 5 kW motor for different percentage of loadings as number of motors are higher than other capacities of motors.

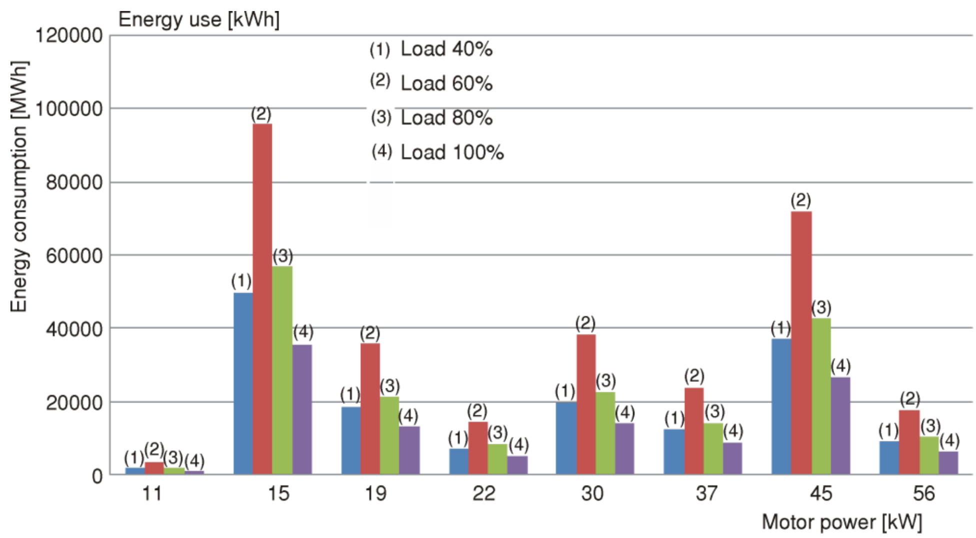

Figure 4. Energy used by different capacity and motor loadings

Using eq. (2) and data shown in tab. 1, energy savings has been estimated and presented in figs. 5 and 6.

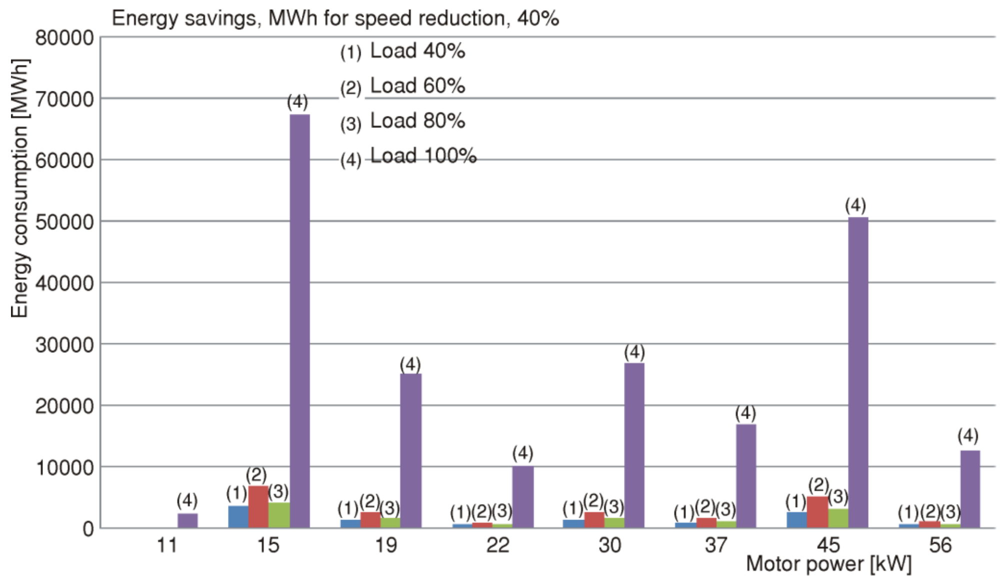

Figure 5. Boiler fan motors energy savings for 40% speed reductions

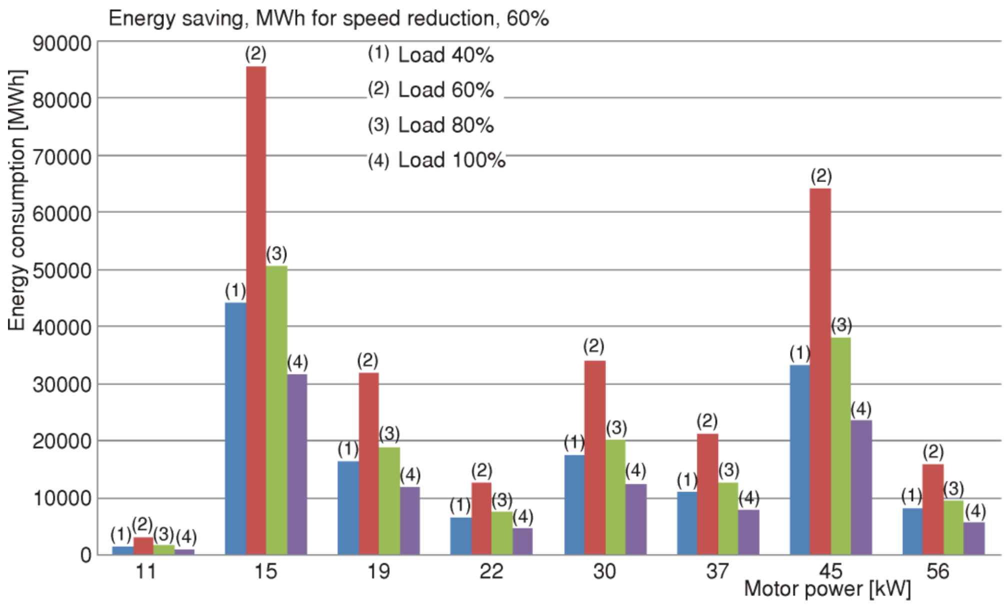

Figure 6. Boiler fan motors energy savings for 60% speed reductions

Similarly, using eq. (3) and data shown in figs. 5 and 6, bill savings has been estimated and presented in figs. 7 and 8.

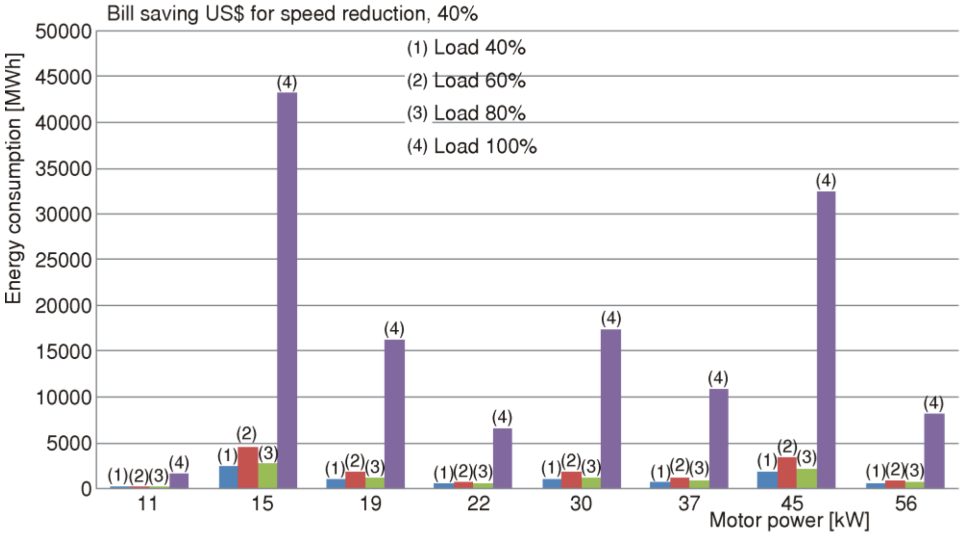

Figure 7. Bill savings for 40% speed reductions

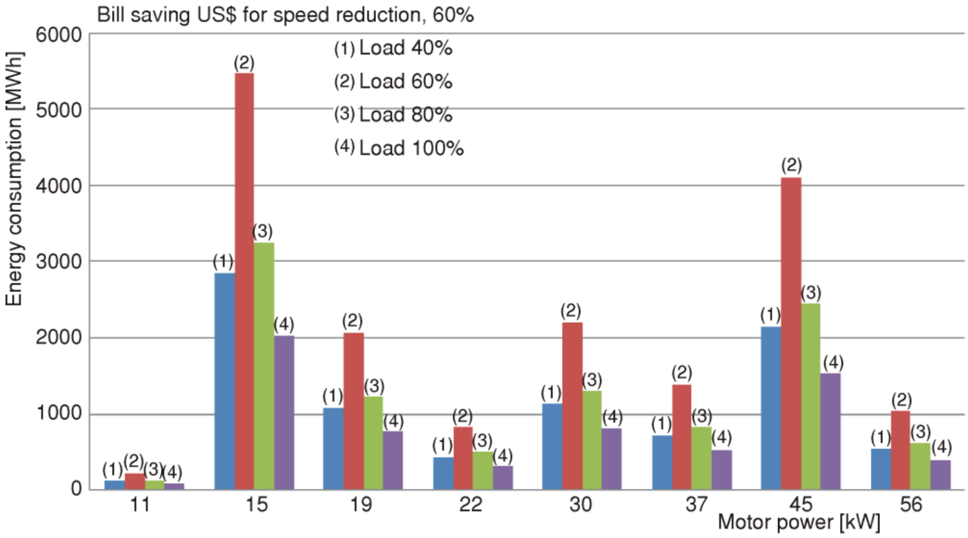

Figure 8. Bill savings for 60% speed reductions

Table 8 summarises the cumilative amount of energy and bill that can be saved for different percentage of speed reduction and motor loadings.

Table 8. Cumilative energy and bill savings for different percentage of speed reductions and motor loadings

Speed reduction	Energy savings [MWh]				Bill savings [US$]			
[%]	Load 40%	Load 60%	Load 80%	Load 100%	Load 40%	Load 60%	Load 80%	Load 100%
40	114,349	220,530	130,685	2,123,624	7,318,335	14,113,933	8,363,812	135,911,944
60	139,412	268,866	159,328	99,580	8,922,354	17,207,397	10,196,976	6,373,110

Using data from tab. 6, payback period for energy savings associated with different percentage of speed reductions has been estimated and presented in tab. 9.

Table 9. Payback period for different percentage of speed reductions using VSD

Motor power [kW]	For 40% speed reduction				For 60% speed reduction			
	Load 40%	Load 60%	Load 80%	Load 100%	Load 40%	Load 60%	Load 80%	Load 100%
11	2.40	1.25	2.10	0.13	1.97	1.02	1.72	2.76
15	0.15	0.08	0.13	0.01	0.12	0.06	0.11	0.17
19	0.15	0.08	0.13	0.01	0.12	0.06	0.11	0.17
22	0.29	0.15	0.26	0.02	0.24	0.13	0.21	0.34
30	0.16	0.08	0.14	0.01	0.13	0.07	0.11	0.18
37	0.16	0.08	0.14	0.01	0.13	0.07	0.12	0.18
45	0.03	0.02	0.03	0.00	0.03	0.01	0.02	0.04
52	0.10	0.05	0.09	0.01	0.08	0.04	0.07	0.11

Using data and formulations presented in [4], fuel energy savings for the has been estimated as:

$$\text{Fuel savings} = \frac{94.5 - 83.5}{94.5} = 11.3\%$$

In this analysis total fossil fuel energy consumption for 48 industries have been found to be 32,503.558 GJ per year based on PTM energy audit data [24, 25]. Based on savings (*i. e.* 11.3%), it has been estimated that about 3,672.902 GJ per year can be saved. Using eqs. (5) and (6), and data from tab. 5, combustion efficiency, energy savings, bill savings, and payback period for oxygen trim has been estimated and presented in tab. 10.

Table 10. Savings from oxygen trim (data for columns 1 and 2 taken from [24])

Excess air [%]	Exhaust temperature [°C]	Combustion efficiency [%]	Savings [%]	Total savings [GJ]	Bill savings [US$]	Payback period [day]
31	350	77.6	16.9	549,310,130	1,098,620,260	0.5103
27	297	77.9	16.6	539,559,063	1,079,118,126	0.5195
26	297	77.9	16.6	539,559,063	1,079,118,126	0.5195
24	295	78.2	16.3	529,807,995	1,059,615,991	0.5291
19	289	78.9	15.6	507,055,505	1,014,111,010	0.5528
20	274	79.5	15	487,553,370	975,106,740	0.5750
23	241	80.7	13.8	448,549,100	897,098,201	0.6249
23	203	82.3	2.2	71,507,828	143,015,655	3.9201
10	146	94.5	–	–	–	–

From the results presented in the tab. 10, it has been found that pay back period is less than half of a day and hence return on investment is immediate. Using eq. (8) and data from tab. 7. and figs. 5 and 6 (*i. e*. for energy savings at different speed reduction), emission reductions have been quantified and presented in tabs. 11 and 12.

Table 11. Emission reduction [kg] for 40% speed reduction

For 40% load				For 60% load			
CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO
680,136	4071	1,918	414	1,311,226	7,849	3,698	798
18,164,987	108,736	51,225	11,049	35,032,260	209,703	98,791	21,308
6,813,371	40,785	19,214	4,144	13,139,787	78,655	37,054	7,992
2,728,051	16,330	7,693	1,659	5,261,420	31,495	14,837	3,200
7,263,793	43,481	20,484	4,418	14,008,600	83,855	39,504	8,520
4,546,752	27,217	12,822	2,765	8,768,700	52,489	24,728	5,333
13,631,747	81,600	38,442	8,291	26,290,085	157,372	74,138	15,990
3,399,679	20,350	9,587	2,068	6,556,631	39,248	18,490	3,988
For 80% load				For 100% load			
CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO
777,227	4,652	2,192	473	12,627,308	75,587	35,609	7,680
20,759,913	124,269	58,543	12,627	337,346,961	2,019,358	951,319	205,185
7,786,281	46,609	21,957	4,736	126,530,822	757,413	356,817	76,960
3,117,916	18,664	8,793	1,896	50,663,377	303,271	142,871	30,815
8,301,263	49,691	23,410	5,049	134,898,147	807,500	380,413	82,049
5,196,359	31,105	14,654	3,161	84,438,961	505,451	238,118	51,358
15,579,068	93,256	43,933	9,476	253,163,239	1,515,434	713,920	153,982
3,885,634	23,259	10,957	2,363	63,137,541	377,941	178,048	38,402

Table 12. Emission reduction for 60% speed reduction

For 40% load				For 60% load			
CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO
828,775	4,961	2,337	504	1,598,495	9,569	4,508	972
22,146,209	132,567	62,452	13,470	42,710,440	255,665	120,443	25,978
8,306,267	49,721	23,424	5,052	16,019,480	95,893	45,175	9,744
3,326,110	19,910	9,380	2,023	6,414,498	38,397	18,089	3,901
8,855,781	53,011	24,973	5,386	17,078,971	102,235	48,163	10,388
5,543,184	33,181	15,632	3,372	10,690,497	63,993	30,147	6,502
16,619,541	99,485	46,867	10,109	32,052,473	191,866	90,388	19,495
4,144,876	24,811	11,689	2,521	7,993,475	47,849	22,542	4,862
For 80% load				For 100% load			
CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO
947,386	5,671	2,672	576	592,054	3,544	1,670	360
25,309,668	151,504	71,373	15,394	15,818,793	94,691	44,609	9,621
9,493,377	56,827	26,771	5,774	5,933,048	35,515	16,731	3,609
3,801,054	22,753	10,719	2,312	2,375,722	14,221	6,700	1,445
10,120,964	60,584	28,541	6,156	6,325,415	37,864	17,838	3,847
6,334,924	37,921	17,864	3,853	3,959,703	23,703	11,166	2,408
18,993,762	113,697	53,562	11,553	11,871,101	71,060	33,477	7,220
4,736,930	28,355	13,358	2,881	2,960,769	17,723	8,349	1,801

Quantification of energy savings with the use of VSD

Lönnberg [29] applied variable speed drive in pumping systems in a hospital and showed huge savings potentials as pumps in a hospital have to operate 24 hours in a week. Author also estimated that $11,855 USD per year can be saved using VSD for pumps in a hospital. At the metal plating facility in Burlington, Vermont, USA, General Dynamics Armament Systems installed ASD along with an energy management control system (EMS) to control the ASD as a unit. They found electricity savings of 443,332 kWh. The project cost $99,400 to implement, and saved $68,600 annually, providing a simple payback period of 1.5 years. The installation also reduced CO_2 emissions by 213,000 kg per year, improved overall productivity, control, and product quality, and reduced wear of equipment, thereby reducing future maintenance costs [30].

Another example of the use of ASD was in the pumping of machine coolant at an USA engine plant. Pressure at the pumps was reduced from 64 psi to 45 psi, average flow cut in half, and power usage reduced by over 50% with no adverse effect on part quality or tool life. Reducing the coolant system pressure also reduced the misting of the coolant, reducing the ventilation requirements and cleaning costs. ASD can also be used in draft fans on coal-fired boilers, instead of dampers. The average electricity savings depend on boiler load, but will typically exceed 60% annually [31].

Yu *et al.* [18] reported that load-based speed control for all-variable speed chiller plants to optimize their environmental performance. Authors found that the application of load-based speed control to the variable speed chiller plant can reduce the annual total electricity use by 19.7% and annual water use by 15.9% relative to the corresponding constant speed plant. Authors also showed that power consumption can be reduced from 13,500 W to 365 W by using variable speed drive

Conclusions

Following conclusions can be made from this study.

- It has been found that maximum amount of energy (*i. e.* 268,865 MWh) can be saved for 60% of motor fan speed reduction for 60% motor loading using VSD. However, it was also found that sizeable amount of energy and bill can be saved for 20% and 40% speed reduction for different loadings.
- It was found that pay back period for using VSD to save fan motor energy to be 0.23 to 5.58 years. It may be stated that use of VSD in fan motor energy saving is economically very viable for motor capacities larger than 15 kW.
- It was also found that 32,503,558 GJ of fossil fuel can be saved for the flue gas temperature reduction as a result of reducing fan motor speed reduction. Flue gas energy savings for oxygen trim system has been estimated and found to be 549,310,130 GJ for 16.9% of excess air reduction with payback period less than a day.
- Study also found that 69,770,744 kg, 134,558,329 kg, 79,738,065 kg, and 49,836,603 kg of CO_2 emission can be avoided for the associated energy savings as a result of energy savings using VSD for 40%, 60%, 80%, and 100% motor loadings.

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