

Article

Comparative Study of Induction Motors of IE2, IE3 and IE4 Efficiency Classes in Pump Applications Taking into Account CO₂ Emission Intensity

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Featured Application: The presented results can be used to evaluate the energy-saving potential and ecological impact of electric motors of various energy efficiency classes in various applications of electric drive.

Abstract: The high energy intensity of the modern industry and the threat of climate change determine the high urgency of increasing the energy efficiency of electric motors. In this paper, energy consumption, energy costs, payback periods, and CO₂ emissions of 75 kW, 4 pole induction motors with direct grid supply in a fixed-speed pump unit are evaluated. Motors of the IE2, IE3, and IE4 efficiency classes according to IEC 60034-30-1 standard are compared in terms of life-time energy savings, payback period, and CO₂ emissions. To carry out the analysis, polynomial interpolation of the data from the available manufacturer datasheets of the motors is used. It concluded that even though the initial investment cost of the IE4-motor is higher than that of IE3-motor, the IE4-motor is more profitable if more than 3 years of operation are considered and also provides significant reductions of CO₂ emissions. The paper presents a calculation method of the aforementioned indicators which can be useful for companies, researchers, and engineers for quick assessment and selection of technical solutions.

Keywords: centrifugal pump; cost savings; energy conversion; energy efficiency; energy efficiency class; energy policies and regulation; induction motor; lifetime cost; throttling control; carbon dioxide emissions; environmental impact assessment; climate change mitigation; low-carbon development; sustainable utilization of resources

1. Introduction

Both inside and outside the European Union, increasing the energy efficiency of household appliances, industrial equipment, and technological processes is a long-term stable trend. According to the European Commission data [1], electric motors consume about 46% of the electricity produced worldwide and up to 70% of the electricity in industrial applications. For this reason, the legislation in the field of mandatory energy efficiency classes of converter-powered motors operating as a part of variable speed drives (VSD) [2] and line-start (direct-on-line) [3] is becoming more and more demanding.

According to the European Commission Regulations [4] from 1 January 2017, in the European Union, all line-start motors with a rated output of 0.75–375 kW should not be less efficient than the IE3 efficiency level. VSD motors should not be less efficient than the IE2 level. The requirements have been updated in the new 2019 European Commission Regulation [5]. According to [5], both line-start

and VSD 2-, 4-, 6-, 8-pole motors with a rated output of 0.12–1000 kW shall not be less efficient than the IE3 level from 1 July 2021. In addition, from 1 July 2023, 2-, 4- and 6-pole motors with a rated output of 75–200 kW shall not be less efficient than IE4 level. In many countries outside the European Union, IE3 motors are also mandatory [6]: Switzerland and Turkey adopt the regulations of the European Union; USA (0.75–200 kW, from 2017); Canada (0.75–150 kW, from 2017); Mexico (0.75–375 kW, from 2010); South Korea (0.75–200 kW, from 2017); Singapore (0.75–375 kW, from 2013), Japan (0.75–375 kW, from 2014), Saudi Arabia (0.75–375 kW, from 2018), Brazil (0.75–185 kW, from 2017).

All aforementioned measures are aimed at the reduction of carbon dioxide (CO₂) emissions, since CO₂ is one of the most dangerous greenhouse gases. Besides energy saving on the consumer side, usage of the sources with high energy conversion efficiency and renewable energy sources are also very important and results in a significant reduction in greenhouse gas emissions [7–9].

Pumps of various types consume about 22% of all electricity produced worldwide [3]. Therefore, studying the opportunities for increasing the energy efficiency of pump units is of current interest.

Centrifugal pumps often do not require their drives to provide a wide speed-range adjustment, a high starting torque, or enhanced dynamic performances. For this reason, induction motors (IMs) fed directly from the mains are commonly used in this application. In this case, the fluid flow is adjusted by throttling. It can be also noted that these IMs are the most common solution in most applications because of the high cost of frequency converters. Thus, the variable-speed drives account only for 22% of the market in Germany [1] and about 20% in Switzerland [10].

Improving the energy efficiency of a pump unit is possible by optimizing the hydraulic network in which the pump operates, applying VSD, optimizing the load distribution (in the case of parallel-running pumps), and by the proper selection of the elements of the pump unit. In particular, electric motors of a higher energy efficiency level can be applied [11]. A large number of works provide comparative studies on the feasibility of pump systems employing motors various of various types (induction motors, synchronous motors with rare-earth magnets on the rotor, synchronous reluctance motors without magnets) [12–15]. However, all these works are dedicated to the analysis of pump units adjusted by VSD. In this paper, the use of electric motors with a higher energy efficiency class is discussed as the most relevant way to increase the energy efficiency of pumps with throttle control.

It can be noted, that according to document [3], IE-levels depend only on the motor efficiency in the rated loading point. However, it is typical for motors in pump applications to operate at underload most of the time. For example, low-power (≤ 2.5 kW) circulator pumps in variable-flow systems have the following typical flow-time profile [16–18]: 25%-flow for 44% of the time; 50%-flow for 35% of the time; 75%-flow for 15% of the time, and only for 6% of the time the pump operates at the rated flow.

Industrial centrifugal water pumps have the following typical flow-time profile [17,18]: 75%-flow for 25% of the time; 100%-flow for 50% of the time, and 110%-flow for 25% of the time. It can be mentioned that the pump efficiency indicator (minimum efficiency index, MEI) also depends on the efficiency of the pump hydraulic part in these three operating points [19].

In [20], the comparison of the energy consumption of 2.2 kW line-start permanent magnet motors (LS-PMSM) and induction motors of IE3 and IE4 classes in a pump unit with throttling control is considered. The annual energy consumption, the annual electricity costs, and the life-cycle cost savings were assessed for these motors. The main purpose of that work was to demonstrate that when deciding which motor to use in variable-flow pump units with the loading cycle according to [16], it is also needed to consider not only the rated efficiency that determines the energy efficiency class of the motor. It is also necessary to take into account the efficiency values of the motor under partial load conditions. Still, in [20], the payback period and CO₂ emissions, depending on the electricity consumed by different motors, were not estimated.

In [21], a comparative analysis of energy consumption is presented for 15 kW induction motors of IE1 and IE2 classes in a pump unit with a throttling control. CO₂ emissions differences were not considered, but the payback period in the case of replacing the IE1-class with the IE2 motor was assessed. However, replacing IE1 motors with IE2 motors is relevant only in some countries.

For example, this measure can be up-to-date in the countries of the Eurasian Economic Union (Russia, Armenia, Belarus, Kazakhstan, and Kyrgyzstan) as the ecodesign legislation of these countries [22] allows using IE1-motors until 1 September 2021.

The above overview shows that comparative analysis of energy efficiency indicators and CO₂ emissions depending on the consumed electricity for motors of IE2, IE3, and IE4 classes in high and medium-power, constant flow pump applications with throttle control is still not presented in the literature.

This paper presents the comparison of the main energy efficiency indicators and payback periods of 75 kW, 4-pole inductions motors of the IE2, IE3, and IE4 classes in a fixed-speed pump unit with throttle control. The manufacturer catalog data [23–25] and the data of the typical flow-time profile [17,18] are used for the comparison.

2. Characteristics of the Pump

To assess the motor loading conditions in various loading points of the pump this study uses a polynomial interpolation of data from technical datasheets of the pump and electric motors based on the experimental data. Data of pump Calpeda NMS4 150/400A/A [26] with the rated power P_{RATE} of 75 kW and the rated rotational speed n_{RATE} of 1450 rpm are used for the analysis. The main parameters of this pump are specified in Table 1. Figure 1 shows the head-flow, mechanical power-flow, and efficiency-flow curves of this pump.

Table 1. Nameplate data of the pump.

Parameter	Type	P_{RATE} , W	n_{RATE} , rpm	Q_{BEP} , m ³ /h	H_{BEP} , m	Efficiency, %
Value	NMS4 150/400A/A	75,000	1450	352	50.3	81

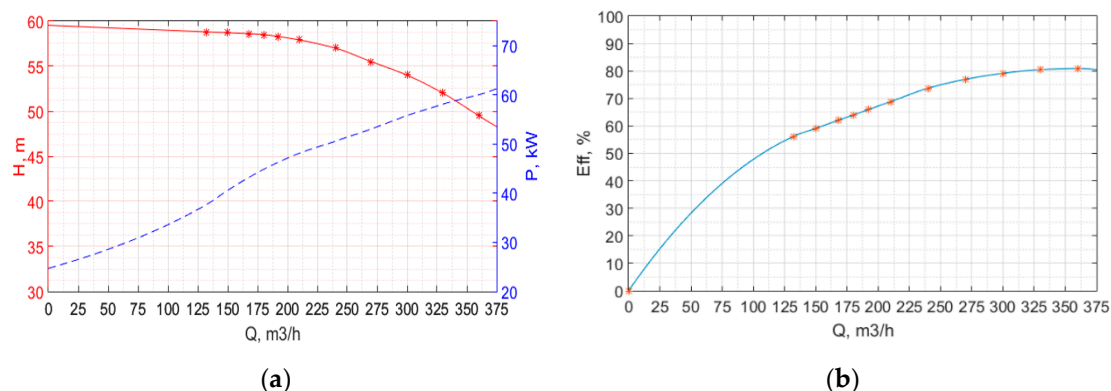


Figure 1. Pump interpolated curves and initial points: (a) Q - H curve of the pump and dependence of the pump power on water flow; (b) dependence of the pump efficiency on water flow.

3. Calculation Method for Assessment of the Energy Consumption of the Pump Unit

The electrical power consumed from the grid is calculated using the interpolated pump mechanical power and interpolated motor efficiency according to Formula (1):

$$P_{1.i.m} = P_{mech.i.m} / \eta_{M.i.m} \quad (1)$$

where $P_{mech.i.m}$ is the pump mechanical power; $\eta_{M.i.m}$ is the efficiency of m -th motor in i -th loading point. Second-order polynomial interpolation of the motors' loss curves was used for the calculation of the efficiency at each loading point. As it is shown in [27], losses as a function of the load may be described by a second-order polynomial curve, the coefficients of which can be calculated using the

efficiencies at three standard loading points (50%, 75%, 100%) provided by the manufacturers of the electric motor.

The electricity consumed per annum by one of the considered motors assuming the flow-time diagram shown in Figure 2 is determined using the Formula (2), where t_{Σ} is the total time of the operating cycle (24 h) and t_i is the operating time of the pump in i -th loading point (see Figure 2).

$$E_{y,m} = 365 \cdot t_{\Sigma} \cdot \sum_{i=1}^3 \left(P_{1.i.m} \cdot \frac{t_i}{t_{\Sigma}} \right). \quad (2)$$

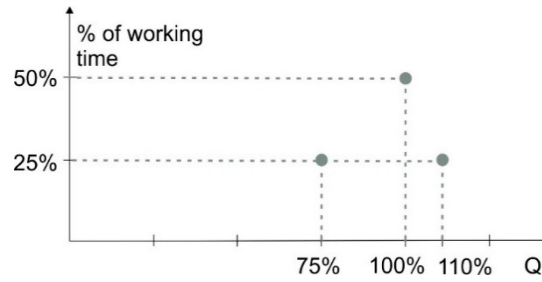


Figure 2. Flow-time profile for constant flow systems [17,18].

4. Calculation Method for Assessment of the CO₂ Emission Intensity

The annual CO₂ emissions were estimated using the CO₂ emissions factor for electricity consumption (EFE; it is 418.8 g/kW·h for Germany according to the data [28]) as follows:

$$CDE_{y,m} = E_{y,m} \cdot EFE. \quad (3)$$

The avoided annual emissions were calculated according to formula (4):

$$\Delta CDE_{y,3m} = CDE_{y,3} - CDE_{y,m}. \quad (4)$$

$E_{y,m}$ in formula (2) can be considered as the “final energy” according to [29]. The generation and transmission of the “final energy” demand a corresponding value of “primary energy” from energy sources [30]. The primary energy factor (PEF) is used for calculations of primary energy and it characterizes the averaged efficiency of the primary energy conversion into the final energy [30]. According to Directive 2012/27/EU [29], a default PEF of 2.5 is applicable. However, this value of PEF is under discussion in [31] and one of the main issues is the need to revise the coefficient 2.5. For example, according to [31], PEF is assumed to be 1.8–2.2 depending on the calculation method. In [32] PEF was also estimated and assumed to be 2.21 for European conditions. Taking into account $PEF = 2.2$, the annual $CDE^*_{y,m}$ and avoided CO₂ emissions $\Delta CDE^*_{y,3m}$ were recalculated according to Formulae (5) and (6):

$$CDE^*_{y,m} = CDE_{y,m} \cdot PEF. \quad (5)$$

$$\Delta CDE^*_{y,3m} = CDE^*_{y,3} - CDE^*_{y,m}. \quad (6)$$

5. Calculation Method for Assessment of the Lifecycle Costs and Cost Savings

The electricity cost (in Euro) at the tariff GT for non-household consumers in Germany equal to 0.188€/per kWh [33] is calculated according to (7):

$$C_{y,m} = E_{y,m} \cdot GT. \quad (7)$$

To compare the cost of the electricity consumed per annum in the case of different motors, the differences in the costs were calculated at the considered flow-time profile according to formula (8).

$$S_{y,31} = C_{y,3} - C_{y,1}; S_{y,32} = C_{y,3} - C_{y,2}; S_{y,21} = C_{y,2} - C_{y,1}. \quad (8)$$

The pump lifetime cost often consists mostly of the energy cost (more than 50–60%) [34,35]. According to [34,35] the duration of the life cycle of pump units is about 15–20 years. For this reason, in this study, it is assumed the estimated pump lifetime of $n = 20$ years. The net present value (NPV) of the energy cost over the entire service life is estimated according to:

$$C_{LCCen,m} = C_{y,m}/(1 + (y - p))^n \quad (9)$$

where p is the expected inflation per annum (defined as 0.02); y is the interest rate (defined as 0.04) [34,35].

The lifetime cost saving of m -th motor relative to the IE2-motor ($m = 3$) is calculated as follows:

$$\Delta C_{LCCen,3m} = C_{LCCen,3} - C_{LCCen,m}. \quad (10)$$

In the case of replacing the IE2-motor ($m = 3$) with the IE4 ($m = 1$) or the IE3-motor ($m = 2$), the payback time T_m of the m -th motor is calculated as following:

$$T_m = C_{iic,m}/S_{y,3m} \quad (11)$$

where $C_{iic,m}$ is the initial investment costs of the motors, according to data of [36].

6. Results and Discussions

Table 2 shows the pump parameters in the points of the pump duty cycle according to the characteristics of the manufacturer's catalog [26].

Table 2. Pump loading cycle parameters.

No. of Loading Points (<i>i</i>)	1	2	3
Q_i , %	75	100	110
Q_i , m ³ /h	264.0	352.0	387.2
$H_{pump,i}$, m	55.8	50.3	47.2
$\eta_{pump,i}$, %	76.22	81.00	79.85
$P_{mech,i}$, W	52,538	59,520	62,421
$P_{mech,i}$, %	70.05	79.36	83.23

Table 3 and Figure 3 show the motor efficiency in the loading points specified in the catalog (50%, 75%, and 100% of the rated motor output power) [23–25]. In addition, Table 3 specifies the interpolated motor efficiency in the points of the pump duty cycle (75%, 100%, and 110% of the rated flow). All motors under consideration have identical frame size 280S/M and identical mounting dimensions.

Table 3. Catalog and interpolated efficiencies of 75 kW 4-pole electric motors.

<i>m</i>	Type of Motor, IE Class	Catalog Efficiency, % at the Loads			Interpolated Efficiency $\eta_{M,i,m}$, % in the Loading Points		
		50%	75%	100%	1	2	3
1	IM, IE4	95.5	96.1	96.2	96.05	96.15	96.18
2	IM, IE3	94.5	95.1	95.2	95.07	95.17	95.19
3	IM, IE2	93.8	94.4	94.4	94.37	94.40	94.40

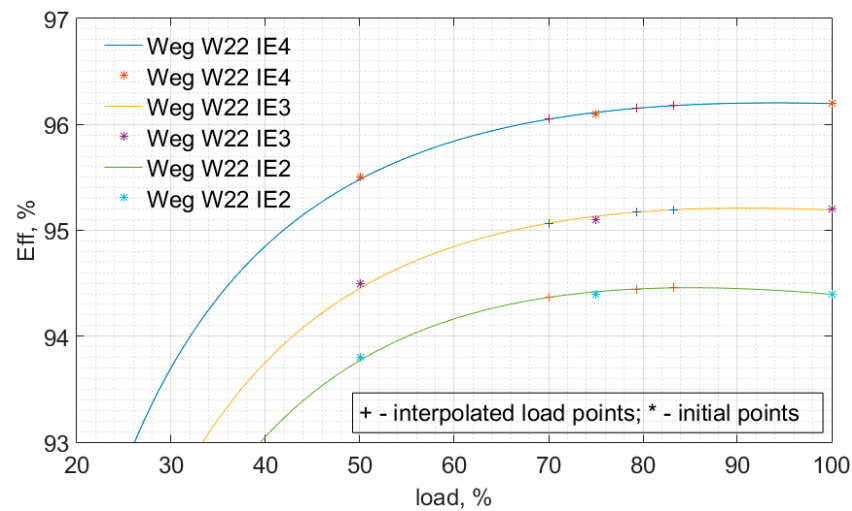


Figure 3. Motors' efficiency interpolated curves and initial points.

Tables 4 and 5, and Figures 4–7 illustrate the results of the energy indicators assessment according to the proposed method, Formulaes (1)–(11).

Table 4. Energy consumption and cost savings calculation results.

m	Type of Motor, IE Class	$E_{y,m}$, MW·h	$C_{y,m}$, k€	$S_{y,3m}$, €	$C_{LCCen,m}$, k€	$\Delta C_{LCCen,3m}$, k€	$C_{iic,m}$, €	T_m , Years
1	IM WEG W22, IE4	533.05	100.21	1809.4	1638.58	29.59	5246	2.9
2	IM WEG W22, IE3	538.56	101.25	775.0	1655.58	12.59	4035	5.2
3	IM WEG W22, IE2	542.68	102.02	-	1668.17	-	-	-

Table 5. CO₂ emissions calculation results.

m	Type of Motor, IE Class	Emissions Considering the Final Energy		Emissions Considering the Primary Energy	
		$CDE_{y,m}$, Tons	$\Delta CDE_{y,3m}$, Tons	$CDE^*_{y,m}$, Tons	$\Delta CDE^*_{y,3m}$, Tons
1	IM WEG W22, IE4	223.24	4.03	491.12	8.87
2	IM WEG W22, IE3	225.55	1.72	496.21	3.78
3	IM WEG W22, IE2	227.27	-	499.99	-

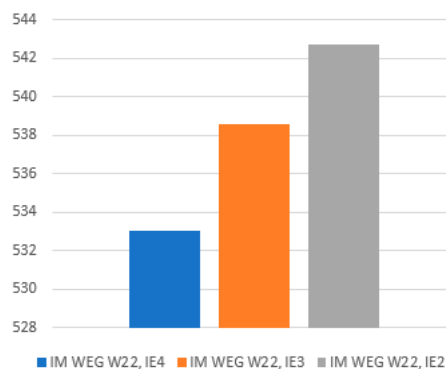


Figure 4. Annual energy consumption $E_{y,m}$ (MW·h).

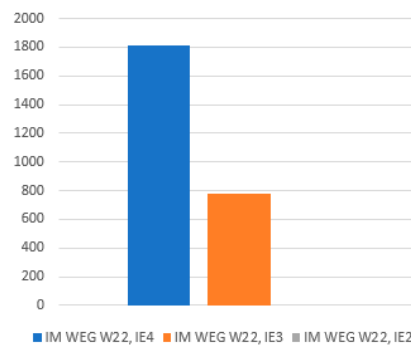


Figure 5. Annual cost savings $S_{y,3m}$ (€).

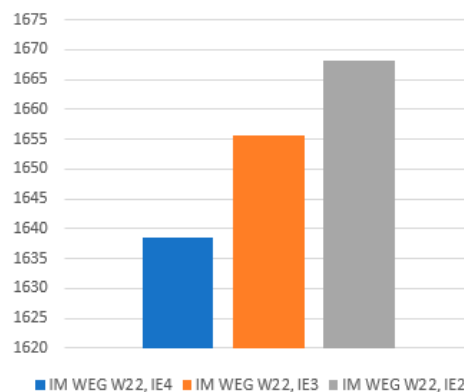


Figure 6. Electricity lifecycle cost $C_{LCCen,m}$ (k€).

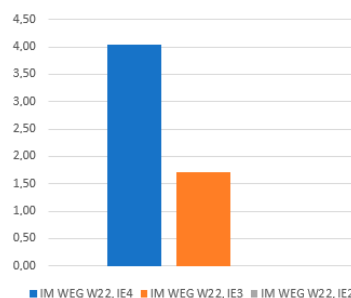


Figure 7. Annual avoided CO₂ emissions $\Delta CDE_{y,3m}$ (tons).

In Table 5 sign “*” indicates the application of the PEF factor to the values without “*”.

In the case of replacing the IE2-motor with the IE4 motor as a part of the pump unit during a planned renovation, the 20 years energy saving is 192.6 MW·h, which saves 29,590€ for the 20 years; the payback period is 2.9 years. In the case of the IE3 motor, the 20 years energy saving is 82.4 MW·h, which saves the 20 years cost for 12,590€, and the payback period is 5.2 years. Therefore, it can be concluded that replacing the IE2-motor with either the IE3-motor or IE4 motor is a feasible solution. Even though the initial investment cost of the IE4-motor is higher compared to the IE3-motor, the IE4-motor is also more profitable if 3–5 years of the operating period is considered.

It should be mentioned that replacing the IE2-motor with IE4-motor leads to avoiding 8.87 tons CO₂ emissions per annum and replacing the IE2-motor with IE3-motor gives only 3.78 tons avoided CO₂ emissions per annum. It can be concluded that although IE4 motor is 30% more costly than IE3 motor (see Table 4) the avoided emissions are $8.87/3.78 = 2.35$ times higher that is very significant.

7. Conclusions

In this paper, the comparative analysis of the energy efficiency indicators and payback periods of the 75 kW, 4-pole induction motors of the IE2, IE3, and IE4 efficiency classes in the fixed-speed

pump unit is carried out. The calculations are based on the manufacturers of the pump and electric motors datasheets. The hydraulic flow variation in the range of 75–110% of the rated pump value is considered. The payback period is assessed in the case of replacing the motor as a part of the pump unit during a planned renovation. The initial investment cost of the IE4-motor is higher comparing to the IE3-motor. However, the payback period of the IE4-motor is only 2.9 years and much shorter than that of the IE3 motor. Therefore, even with the higher initial investment cost, the IE4-motor is significantly more profitable. It should be highlighted that the proposed technical solution is especially relevant considering the requirements of the European Commission Regulation [5], according to which, the use of IE4-class motors for a range of the rated power above 75 kW is mandatory from 1 July 2023. The replacement of the IE2-motor also results in a significant reduction in CO₂ emissions. It is 8.87 tons per annum in the case of the IE4-motor and 3.78 tons per annum in the case of the IE3-motor. In addition, the paper presents the calculation methods for energy consumption, energy savings, cost savings, and carbon dioxide emission intensity which can be useful for companies, researchers, and engineers for quick assessment and selection of technical solutions.

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Abbreviations

IE	International efficiency
IEC	International Electrotechnical Commission
VSD	variable speed drive
CO ₂	carbon dioxide
IM	induction motor
MEI	minimum efficiency index
LS-PMSM	line-start permanent magnet motors
BEP	best efficiency point
CDE	carbon dioxide emissions
EFE	CO ₂ emissions factor for electricity consumption
PEF	primary energy factor
NPV	net present value

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