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Optimizing the economic evaluation method for calculating the total owning cost of induction motors

Ayman Agha[1], Khaled Alzaareer[2], Hudefah Alkashashneh[2]
[1]Department of Renewable Energy Engineering, College of Engineering, Amman Arab University, Amman, Jordan
[2]Department Energy Engineering, School of Engineering Technology, Al Hussein Technical University, Amman, Jordan

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ABSTRACT

This paper presents an approach for estimating the total ownership cost (TOC) of induction motors (IMs) by applying five different economic evaluation methods, each based on specific assumptions. These methods are examined and compared in detail to demonstrate the difference in their implementation and outcomes. In addition to the technical data of the analyzed IM, the methods also consider significant economic factors that affect TOC assessments, such as electricity tariffs, initial investment cost, operating hours, discount rate, and the anticipated lifespan. The proposed approach offers a practical tool to support decision-making when selecting the most economical among different alternatives offered by various manufacturers or venders. A numerical example is presented to demonstrate the application of the proposed work, including detailed calculations with results summarized in tables. The paper concludes by offering practical guidance on selecting the most appropriate economic method for the evaluated scenarios of IM, offering direction to site engineers and decision-makers in balancing technical aspects with long-term economic considerations. The calculation is straightforward and can be performed using standard mathematical tools, illustrating how various factors influence costs and enhancing the reliability of the result. For large-scale analyses, MATLAB provides additional computational efficiency and scalability.

Corresponding Author:

Ayman Agha
Department of Renewable Energy Engineering, College of Engineering, Amman Arab University
Amman, Jordan
Email: a.agha@aau.edu.jo

1. INTRODUCTION

Induction motors (IMs) have gained popularity since the dawn of the industrial era. Often dubbed the workhorse of industry, they are valued for their robustness, simple construction, and minimal maintenance requirements. Selecting the appropriate IM improves system efficiency and reduces the total ownership cost (TOC). Electric motors account for approximately 68% of the total electricity used in industrial sectors, with nearly 90% of electric drive systems powered by IMs [1]. Therefore, the proper design, selection, and assessment of IMs are critical for reducing operational costs and enhancing overall system efficiency. Several researchers have introduced different approaches and methodologies to assess the technical and economic aspects of IMs. For example, the work in [2] presents control and optimization strategies to minimize energy losses and enhance sustainability. Dinolova *et al*. [3] outline practical measures for improving overall system efficiency. Based Viorel and Crăciunaș [4], a novel winding configuration is introduced to optimize magnetic flux distribution to reduce power losses. To achieve improved performance under varying load conditions, a quasi-sliding mode controller is implemented in [5]. An adaptive neuro-fuzzy inference system (ANFIS) is employed in [6]. Zhang *et al*. [7] focused on the fault diagnosis of IMs. The detection of faults and the evaluation of load oscillations are investigated in [8]. A stator-rotor fault diagnosis model using the time-frequency domain is proposed in [9]. To classify the normal and abnormal operating conditions of the IM, real-time monitoring and fault detection are implemented in [10]. Computational methods for bearing fault detection, facilitating predictive maintenance and minimizing IM downtime, are provided in [11].

Various techniques and approaches have been proposed to improve the efficiency of IMs. Torrent *et al*. [12] evaluates the energy efficiency, economics, payback period and net present value (NPV) of IM. According to Sheianov *et al*. [13], a new non-intrusive approach is proposed to estimate the load and efficiency of IMs, allowing for accurate assessment without interrupting motor operation. Deveci and Ayçiçek [14] focused on enhancing the dynamic response and stability of single-phase IMs. Meanwhile, the work presented in [15] aims to optimize IM design to reduce energy losses, comply with international efficiency standards, and minimize environmental impact. According to Ekop *et al*. [16], a real-time fault detection system used for IM protection. Additionally, Sarac *et al*. [17] focuses on enhancing the safety of IMs, reducing the risk of failures, and improving overall operational efficiency.

The economic aspects of IMs are examined in [18] through an analysis of energy consumption and maintenance costs over the motor's operational lifespan. Baniyounis *et al.* [19] evaluate IM economics using financial metrics, including NPV and equivalent annual cost (EAC), to optimize long-term economic returns. In contrast, [20] assesses the TOC of IMs based on nameplate specification and capital investment. The researcher in [21]-[24] examined the influence of capital and ownership structures on corporate performance, alongside technical challenges, and social-technical considerations associated with optimization methods.

In practice, the calculation of the TOC of IMs often varies due to the use of different economic evaluation methods. These methods differ in how they account for the annual capital and energy losses cost, which can significantly impact the final TOC estimation and the decision on which motor is more cost-effective in the long run. The selection process becomes even more complex when competing offers have similar prices and manufacturers maintain comparable reputations.

Unlike prior studies, this work evaluates five economic assessment methods under diverse operating scenarios to identify the most suitable TOC-based approach for IMs. The findings confirm that motor selection based solely on initial capital cost is insufficient, as neglecting other cost components can result in technical and economic inefficiencies. Accordingly, applying a single TOC evaluation method to all applications may produce inaccurate assessments. Notably, the TOC methods used to evaluate motors intended for short-term operation differ fundamentally from those used for motors installed in industrial plants, which are required to operate continuously throughout their service life. The proposed framework, supported by dedicated software, simplifies the analysis and enhances the result reliability. In addition, a formulation previously developed by the main author is used to calculate motor energy losses and estimate the equivalent annual energy losses, expressed in terms of equivalent loss time per year.

The paper is arranged as follows: section 2 outlines the problem, section 3 focuses on the determination of IM losses, section 4 examines the impact of economic evaluation methods on IM TOC, and section 5 provides a numerical example. Comparative analyses and conclusions are presented in sections 6 and 7, respectively.

2. PROBLEM OUTLINE

The purpose of this research is to determine the optimal economic method for assessing the TOC of IMs. These include capital cost, annual energy cost, operational costs, maintenance costs, and energy loss cost. The mathematical formulation of the problem involves finding the optimal solution C_{opt} from a set of feasible solutions obtained from several alternative calculations of $\{\mathrm{C_{i.IM}}\}$, as presented in (1)*:*

$$\mathrm{C_{opt.}} \in \{\mathrm{C_{i.IM}}\} \tag{1}$$

The solution is subjected to the inequality constraint that the IM's loading power P_L [kW] must not exceed its nominal rated power P_n, as introduced in (2):

$$P_n \geq P_L \tag{2}$$

The total cost $C_{i.IM}$ of the i-th IM is calculated as the sum of its capital cost ($C_{c.IM.}$), energy loss cost (C_{losses}), operational cost ($C_{operational}$), maintenance cost ($C_{maintenance}$), and availability cost ($C_{availability}$), as given by (3):

$$C_{i.IM} = C_{c.IM.} + C_{losses} + C_{operational} + C_{maintenance} + C_{availability} \tag{3}$$

Availability cost, or downtime cost, occurs when IM replacement interrupts operations. It is significant in cases of unexpected motor failure requiring immediate replacement, reducing system production. If replacement occurs during a planned shutdown, the cost could be negligible. Maintenance and operational costs of a new motor typically have a minimal impact on motor selection and the choice of economic evaluation method. Hence, for simplicity, the last three terms in (3) are omitted, yielding the objective function becomes as presented in (4):

$$C_{i.IM} = C_{c.IM.} + C_{losses} \quad (4)$$

The capital cost of an IM $C_{c.IM}$, includes the purchase price and all expenses for transportation, supervision, installation, testing, and commissioning required to make the motor operational. Active energy loss cost C_{losses} is calculated by multiplying the unite energy price C_e [$/kWh] by the total energy losses ΔE [kWh], (i.e., $C_{losses} = C_e \cdot \Delta E$). Total losses include both no-load ΔE_{NLL} and on-load E_{LL} losses, as shown in (5):

$$\Delta E = \Delta E_{NLL} + \Delta E_{LL} \quad (5)$$

By multiplying the energy losses in (5) by the unit price of energy C_e, the total cost of active energy losses C_{losses} is obtained. This relationship is mathematically represented in (6):

$$C_{losses} = C_e \cdot (\Delta E_{NLL} + \Delta E_{LL}) \quad (6)$$

Here, $f\{C_{i.IM}\}$ is the set of all possible solutions [$], C_{opt} denotes the optimal solution [$], $C_{c.IM.}$ is the IM capital cost [$], $C_{i.IM}$ represents the TOC of the ith IM [$], C_{losses}, $C_{availability}$, and $C_{maintenance}$ denote the costs of the active energy losses, availability, and maintenance, respectively [$], [$], is the cost [$], $C_{maintenance}$ represents the maintenance cost [$], and P_n and P_L are the nominal power and mechanical power load of the IM [hp or kW].

3. DETERMINATION OF LOSSES IN INDUCTION MOTORS

The flow of the current in an IM results in power losses within the machine windings, commonly referred to as load loses. In addition, losses associated with current flow in the motor core are termed iron losses or no-losses. The determination of these losses are as follows.

3.1. Power losses

This category of losses can be divided into two components, as outlined below. The first component comprises active power losses resulting from the flow active power, while the second component corresponds to active power losses associated with the circulation of reactive power. These components are briefly described below.

3.1.1. Active power losses

The IM exhibits the following active power losses:

- Iron losses (no-load): these occur in the motor core due to main magnetic flux and are present even without load.
- Copper losses (on-load): these results from current in the windings, dissipated as heat.
- Friction and windage losses: friction arises at bearings; windage is due to air resistance on the rotating shaft.
- Stray losses: these are caused by leakage flux in laminations, proportional to rotor current.

3.1.2. Reactive power losses

The flow of reactive power in the IM causes power losses, which can be divided into two types: no-load reactive power losses and on-load reactive power losses. The total active power losses ΔP, resulting from both the active power losses ΔP_p and the reactive power losses ΔP_Q, are represented in (7):

$$\Delta P = \Delta P_p + \Delta P_Q \quad (7)$$

Active power losses resulting from reactive power flow can be determined using an equivalent coefficient. The IM loading varies with changes in mechanical load during load during process cycle. At light loads, the power factor can drop significantly, sometimes to 0.4 or lower, increasing reactive power consumption. Consequently, reactive power contributes to active power losses in IMs. The equivalent coefficient converts reactive power losses into active power losses and is measured in [kW/kVAR], typically, these losses represents around 10% of the total power [25], or they may be treated as separately segregated losses, as discussed in [26]. Since this coefficient applies uniformly to all evaluated motors, it can be neglected for simplicity in (7) without introducing significant error. Thus, total power losses of IM are, in this case, approximately equal to active power losses only, as shown in (8):

$$\Delta P \cong \Delta P_p \tag{8}$$

Therefore, the active power losses of the IM for any mechanical load P_L up to the nominal power P_n can be expressed as in (9), [19]:

$$\Delta P = \Delta P_{Fe} + \Delta P_{Cu} \cdot \left(\frac{P_L}{P_n}\right)^2 \tag{9}$$

Here, ΔP_{Fe} refers to the core (no-load) losses of the IM [kW], ΔP_{Cu} denotes the copper (on-load) losses [kW], P_L represents the mechanical load of the IM [kW], and P_n indicates the nominal power of the IM [kW].

The core losses ΔP_{Fe} and copper losses ΔP_{cu} in (9) may not be indicated on the IM nameplate but are usually provided by manufacturer's technical data sheet for a given motor type and power rating. If these values are unavailable or difficult to obtain, the total power losses $\Delta P(t)$ of the IM can be calculated using commonly available nameplate data such as nominal voltage, nominal current, power factor, and nominal power. By applying the approximate relation given in [19], $\Delta P(t)$ can be determined as shown in (10):

$$\Delta P(t) = 0.28\,\Delta P + 0.72\,\Delta P \cdot \left(\frac{P_L}{P_n}\right)^2 \tag{10}$$

In (10), the total power loss ΔP can be obtained from the general efficiency (η) expression, as given in (11):

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_n}{P_n + \Delta P} \tag{11}$$

By rearranging (11), the total power losses can be expressed in terms of efficiency and nominal power, as shown in (12):

$$\Delta P = P_n\left(\frac{1}{\eta} - 1\right) \tag{12}$$

In (13) provides the general expression for the active power drawn by the motor, which used to determine the input power in (11):

$$P_{in} = \sqrt{3} \cdot V_n \cdot I_n \cdot cos\,(\theta) \tag{13}$$

Here, P_{in} denotes the input (consumed) active power of the IM [kW], $P_{out} = P_n$ represents the nominal (rated) output power of the IM [kW], ΔP indicates the nominal active power losses of the IM [kW], and $\Delta P(t)$ is the total active power losses at a given load [kW], while V_n denotes the nominal voltage [V], I_n is the nominal current of the IM [A], $cos\,(\theta)$ is the power factor of the IM [dimensionless], and η is the efficiency of the IM [dimensionless].

3.2. Energy losses

The energy losses ΔE are calculated by integrating the power losses ΔP(t) over a given period T, typically measured in hours [h], such as a month or a year. When the time-dependent power losses values are arranged in descending order from $\Delta P_{max.}$ to $\Delta P_{min.}$, as illustrated in Figure 1, the areas under the dotted and solid lines are equal. This relationship is expressed mathematically in (14):

$$\Delta E = \int_0^T \Delta P(t) \cdot dt = \Delta P(t) \cdot T = \Delta P_{max} \cdot \tau \tag{14}$$

The total annual operating hours of the IM, denoted as T [h/year], account for full load. Here, τ [h/year] donates the equivalent annual loss corresponding to the loading periods. Substituting (10) into (14), yields (15):

$$\Delta E = 0.28\,\Delta P \cdot T + 0.72\,\Delta P\,(\frac{P_L}{P_n})^2 \cdot \tau \quad (15)$$

Based on the relationship between the equivalent load loss time τ and the loss factor (LLF) [27] as (16):

$$\tau = LLF \cdot T \quad (16)$$

The LLF is a coefficient used to determine the total energy loss ΔE. The total energy loss ΔE can be determined by multiplying the maximum power loss ΔP_{max} by the total number of load intervals *T*. By substituting (16) into (14), and (17) is obtained.

$$E = \Delta P_{max.} \cdot T \cdot LLF \quad (17)$$

The relationship between the load factor *LF* and *LLF* is given by the computational formula in [28], as (18):

$$LLF = (1 - k) \cdot LF^2 + k \cdot LF \quad (18)$$

The coefficient *k* in (18) ranges from 0 to 1. (e.g., 0.2 in the UK, 0.3 in the USA, 0.33 in Poland); in this study adopts *k*=0.33. The LF is defined as the ratio of the equivalent operating hours T_{eq} to the total operating hours T over the analyzed period [29], as given in (19) and shown in Figure 2.

$$LF = \frac{T_{eq}}{T} \quad (19)$$

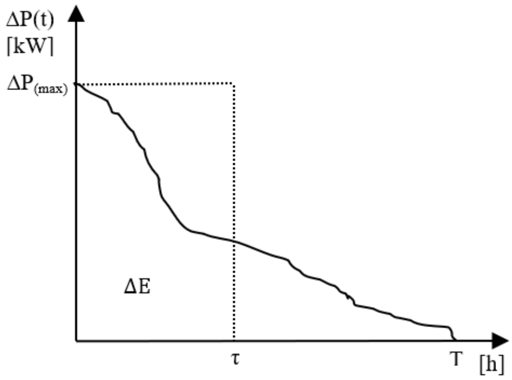

Figure 1. Equivalent loss time

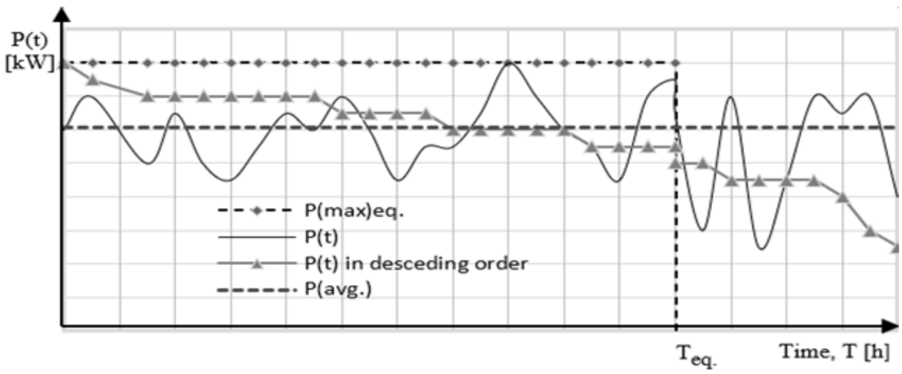

Figure 2. Maximum, average, and instantaneous power [29]

3.3. Determination of equivalent working hours

When the load on an IM varies over time, it can be represented as equal integrated segments arranged in descending order, from the highest load power $P_{max.}$ to the lowest P_{min}, as shown in Figure 2.

Once the areas under the solid curve and dotted line are equal, the active energy E consumed during the equivalent time T_{eq} can be calculated using (20):

$$E = \int_0^T P(t)\, dt = P_{max.} \cdot T_{eq} \quad (20)$$

Earlier works [19], [29]-[31] presented a formula to determine the equivalent operating hours over a one-month period, as expressed in (21):

$$T_{(w/m)eq.} = 2 \cdot D_{(w/y)} \cdot \left(\frac{n_s}{3} + \frac{3-n_s}{3} \cdot \frac{A_{p\,(aw)}}{A_{p(w)}}\right) + 2 \cdot (365 - D_{(w/y)}) \cdot \frac{A_{p\,(aw)}}{A_{p(w)}}) \quad (21)$$

The total equivalent operating hours T_{eq}, for the evaluation period can be determined by multiplying the number of months N by the total equivalent working hours per month $T_{(w/m)eq.}$, as expressed in (22):

$$T_{eq} = N \cdot T_{(w/m)eq} \quad (22)$$

Finally, by substituting (22) into (19) and using (16)–(18) to replace T and τ, the solution given in (15) is obtained. This form of (15) serves as the general formula for calculating the active energy loss over a specified period, typically one year.

Here, $Ap_{(w)}$ represents the total active energy consumed (day and night) over one month [kWh], $A_{p(aw)}$ refers to the active energy consumed after the operational hours in one month [kWh], and $D_{(w/y)}$ denotes the number of working days per year, excluding holidays, shutdowns, and weekends. E is the total consumed active energy over the year [kWh/year], LLF indicates the load loss factor [dimensionless], $cos\ (\theta)$ is the power factor of the IM [dimensionless], and LF refers to the load factor [dimensionless]. $n_{(h/m)}$ represents the number of hours in one month, n_s stand for the number working shifts per day, N is the number of months ($1 \leq N \leq 12$; N=12 for a full year), $T_{(w/m)eq}$ is the equivalent working hours in one month [h/month], T_{eq} donates the equivalent working hours for the analyzed period [h], and T indicates total number of hours for the analyzed period, τ denotes the annual equivalent loss time [h/year], $P_{(avg.)}$ represents the average consumed active power [kW], $P_{max.}$ is the maximum consumed active power [kW], and $P_{min.}$ refers to the minimum consumed active power [kW].

4. EVALUATING ECONOMIC METHODS' IMPACT ON IM TOC

The annual TOC of the i[th] IM comprises the capital cost and the cost of energy losses [32], as presented in (23):

$$TOC = C_{c.IM.} + C_e \cdot \Delta E_i \quad (23)$$

The resulting TOC from this equation may vary depending on the assumptions used during the calculation process. These assumptions include the method of amortizing the IM capital cost, the applied interest rate p, and the cost of electrical energy [$/kWh], as presented hereafter in subsection 4.1.

4.1. Total ownership cost methods for induction motors

The TOC of IMs can be estimated using several economic evaluation methods, with the indifferences outlined below:

Method 1: the TOC of IM is computed as the sum of the motor's initial cost, including all costs necessary to commission the IM, and the cost of energy losses. This approach assumes that both the motor cost and active energy losses cost are evaluated at their initial nominal values without applying any discount. In (23) retains its original form (i.e., $TOC = C_{c.IM.} + C_e \cdot \Delta E_i$.

Method 2: the TOC of the IM is computed as the sum of the discounted capital cost and the cost of active energy losses. with the motor cost discounted using the present value (PV) method [33], [34], as given in (24):

$$TOC = C_{c.IM.} + C_e \cdot \Delta E_i = \left[\frac{C_{c.IM.} \cdot p}{1-(1+p)^{-n}}\right] + C_e \cdot \Delta E_i \quad (24)$$

Method 3: the TOC is determined as the sum of the discounted PVs of the IM capital cost and the active energy cost. Both calculated using the PV method [35], as expressed in (25):

$$TOC = C_{c.IM.} + C_e \cdot \Delta E_i = \left[\frac{C_{c.IM.} \cdot p}{1-(1+p)^{-n}}\right] + \left[\frac{C_e \cdot \Delta E_i \cdot p}{1-(1+p)^{-n}}\right] \quad (25)$$

Method 4: TOC is assessed using the annuity factor method, applying the factor for both, the capital cost and the active energy cost, as given in (26):

$$TOC = C_{c.IM.} + C_e \cdot \Delta E_i = (C_{c.IM.} + C_e \cdot \Delta E_i) \cdot \left[\frac{p \cdot (1+p)^n}{(1+p)^n - 1}\right] \quad (26)$$

Method 5: TOC is evaluated using European Copper Institute method [36], summing the discounted IM capital cost and the discounted active energy cost via two factors (A and B), as expressed in (27):

$$TOC = C_{c.IM.} + A \cdot \Delta P_{Fe} + B \cdot \Delta P_{Cu} \cdot \left(\frac{P_L}{P_n}\right)^2 \quad (27)$$

Factors A and B are calculated as given in (27.1) and (27.2), respectively.

$$A = \left[\frac{(1+p)^n - 1}{p \cdot (1+p)^n}\right] \cdot (C_e \cdot T_{eq} + C_p) \quad (27.1)$$

$$B = A \cdot \left(\frac{P_L}{P_n}\right)^2 \cdot \frac{C_e \cdot \Delta P_{NLL}}{C_e \cdot \Delta P_{LL}} = A \cdot \left(\frac{P_L}{P_n}\right)^2 \cdot \frac{\Delta P_{NLL}}{\Delta P_{LL}} \quad (27.2)$$

The capacity system cost C_p in (27.1) refers to the expenses incurred to produce one additional kilowatt of power.

Here, TOC is the total ownership cost of the i[th] IM [$], $C_{c.IM.}$ donates the annual capital cost of the IM [$], C_e represents the unit price of active energy [$/kWh], C_p refers to the system capacity cost [$/kW], ΔE_i represents the active energy losses [kWh], ΔE_{NLL} represents no-load energy losses [kWh], ΔE_{LL} donates load-dependent energy losses [kWh], p is the discount or interest rate [%], and n is the IM's expected lifetime [years].

5. NUMERICAL EXAMPLE

The assessment is performed based on the following data and general assumptions:

5.1. Technical data of the induction motors

Typically, when intending to purchase new motors, inquiries are sent to various manufacturers, vendors, or suppliers, providing general specifications of the requested motor. Once the offers are received, engineers proceed with the evaluation process, considering both technical and economic aspects while adhering to established good engineering practices. Generally, if the TOC of the received offers are very close, preference is given to manufacturers with a proven reputation for quality and reliability.

To illustrate the economic evaluation process, an example is provided using three IM purchase offers from three different vendors. These offers demonstrate the application of the method, which remains consistent regardless of the number of offers. The input data for the three IM options are summarized in Table 1.

Table 1. Input data for various types of IMs

Motor no	Motor 1	Motor 2	Motor 3
CIM (total cost) [$]	2297	992	2823
Power [kW]	22	22	22
Nominal voltage [V]	400	400	400
Nominal current [A]	42.5	39	40.78
Frequency [Hz]	50	50	50
Power factor [dimensionless]	0.89	0.89	0.85

All remaining technical specifications of the motors are assumed to be the same

General assumption the economic evaluation of IMs is conducted under the following assumptions:

- Working hours: one-shift operation: 8 h/day, 5 days/week with 13 national holidays off. Two-shift: 16 h/day, 5 days/week, 13 national holidays off. Three-shift: continuous operation (one shift off) with two weeks off for annual shutdown.

- Energy consumption after working hours: 25% for one and two-shift modes; 75% for three-shift mode to maintain the process readiness.
- Motor lifetime: 15 years.
- Motors loading: 90% of nominal power (loading factor=0.9).
- Discount rate: 8%, used to convert future cash flows to PV.

The TOC of IMs operating in a single-shift mode, calculated using various economic evaluation methods, is summarized in Table 2.

Table 2. TOC of IMs under different evaluation methods (one-shift operation)

Evaluation method	Method no.1 values not discounted			Method no. 2 only IM annual cost discounted			Method no. 3 all values are discounted			Method no. 4 annuity factor			Method no. 5 based on A and B factors			
Item	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	-	IM 1	IM 2	IM 3
$C_{IM.}$	2297	992	2822	268	116	330	268	116	330	268	116	330	A	3974	3347	3660
$C_{(Losses)}$	1260	614	604	1260	614	604	10787	5251	5168	1260	614	604	B	8461	7128	7794
TOC	3557	1605	3426	1529	729	933	11056	5367	5497	1529	729	933	-	32594	13416	16192

The results in Table 2 can be read as follows: TOC is primarily influenced by electricity tariffs, energy loss costs, capital investment, operating time, discount rate, and equipment lifespan. For the single-shift operation, the equivalent operating hours T_{eq} were calculated as 3702 [h/yr] using (21) and (22), while the LLF was determined as 2269 [h/yr] from (18). Substituting T_{eq} and LLF into (15) yielded the annual energy losses, from which the energy loss C_{losses} was obtained by multiplying with the unit energy price.

The analysis shows that TOC, as in (23), is mainly affected by the cost of energy losses and the capital investment C_{IM} of the IM. This confirms that the ranking of IMs remains consistent across different economic evaluation methods (specifically, IM 2 is the least expensive, followed by IM 3 and then IM 1). Therefore, under single-shift or lower operating conditions, the capital investment of the IM is the dominant factor in minimizing TOC. Table 3 summarizes the outcome of applying multiple economic evaluation methods to IMs under two-shift operation.

Table 3. TOC of IMs under different evaluation methods (two-shift operation)

Evaluation method	Method no. 1 all values not discounted			Method no. 2 only IM annual cost discounted			Method no. 3 all values are discounted			Method no. 4 annuity factor			Method no. 5 based on A and B factors			
Item	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	-	IM 1	IM 2	IM 3
$C_{IM.}$	2297	992	2822	268	116	330	268	116	330	268	116	330	A	5596	4714	5155
$C_{(Losses)}$	1965	956	941	1965	956	941	16816	8186	8056	165	956	941	B	11917	10039	10978
TOC	4261	1948	3763	2233	1072	1271	17084	802	8385	2233	1072	1271	-	44968	18490	21653

By using the same procedure as for Table 2, the TOC results for the two-shift operation are presented in Table 3, with T_{eq}=4875.2 [h/yr] and LLF=3800 [h/yr]. The ranking of IMs remains consistent across economic evaluation methods: IM 2 is the least expensive, followed by IM 3, and then IM 1. Thus, in this case as well, the capital investment of the IM dominates the TOC, assuming that all other influencing factors remain constant. The results for IMs operating in a three-shift mode, evaluated using various economic methods, are shown in Table 4.

Table 4. TOC of IMs under different evaluation methods (three-shift operation)

Evaluation method	Method no. 1 all values not discounted			Method no. 2 only IM annual cost discounted			Method no. 3 all values are discounted			Method no. 4 annuity factor			Method no. 5 based on A and B factors			
Item	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	IM 1	IM 2	IM 3	-	IM 1	IM 2	IM 3
$C_{IM.}$	2297	992	2822	268	116	330	268	116	330	268	116	330	A	8675	6351	6945
$C_{(Losses)}$	3603	1754	1726	3603	1754	1726	30836	15011	14773	3603	1754	1726	B	18472	13524	14789
TOC	5899	2745	4548	3871	1870	2056	31105	15127	15102	3871	1870	2056	-	68440	24564	28190

The results in Table 4 indicate that the TOC ranking is similar to the results obtained in Tables 2 and 3 when applying Methods 1, 2, 3, and 5 (subsection 4.1). The only exception occurs with Method 4, where the ranking is IM2 is the least expensive, followed by IM3, and then IM1. Therefore, based on the IM data in Table 1, it can be concluded that the capital investment for each IM and the cost of energy are the dominant factors in minimizing TOC, regardless of the operation mode. However, this outcome may vary if other influencing factors in (23) are altered.

6. COMPARATIVE ASSESMENT OF ECONOMIC EVALUATION METHODS

The objective of this study is to identify the IM with the lowest TOC using different economic evaluation methods. When motor input data are constant, TOC is influenced by factors such as efficiency, energy tariffs, capital cost, operational hours, discount rate, and expected lifespan. To determine the least expensive motor, five evaluation methods were applied under one, two, and three-shift operation modes. The results are presented in Tables 2 to 4, with key findings for each method discussed below.

First, Method 1 shows that, regardless of whether the IM operates in a one-shift, two-shift, or three-shift mode, the primary factors influencing the TOC are the initial purchase cost and the annual energy loss costs. The simplicity of calculating TOC using (23), without discounting input values, makes this method particularly suitable in cases where the motor is expected to be used temporarily, generally for a duration of several months to three years, such as during the project construction, after which the equipment is disposed of as salvage.

Second, Method 2 considers a situation in which only the capital cost of the IM is amortized, whereas the energy loss costs during the evaluation period are not discounted, regardless of the operating mode. This approach is recommended when the initial purchase cost of the IM is considerably higher than the annual cost of energy losses. In such case, the amortized capital cost becomes the dominant criterion for selecting the motor.

Third, Method 3 assumes that both the capital cost of IM and the energy loss costs throughout the motor's lifetime are discounted. This method is therefore appropriate for industrial facilities where the motor is expected to operate over its full-service life, providing more realistic assessment, particularly under three-shift operating conditions.

Fourth, Method 4 evaluates a scenario in which both the capital cost and the energy loss costs are discounted using the annuity factor, this approach is recommended when, in addition to identifying the motor with the lowest TOC, it is necessary to estimate the financial reserves required to replace the motor at the end of its service life.

Finally, Method 5 demonstrates the TOC using predefined factors (A and B). This approach allocates a substantial financial reserve for purchasing a replacement motor at the end of its service life and is recommended when a significant increase in motor prices is expected in the future.

7. CONCLUSION

Most previous studies on IMs maily foucs on thier technical performance. In contast this paper exames motor selection from an economic standpoint using the TOC criterion. Five economic evaluation methods are interduced, taking into account key parameters such as operating hours, capital cost, energy price, energy losses, motor lifespan, and the discount rate. The results indicates that no single method is universally superior; insted each method is sutable for particular operating conditions and underlying assumptions.

The illustrative case study, which considered only operational time, capital cost, and energy price, showed that capital cost of the IM is the dominanting factor in TOC evaluation for the presented example, under the simplified assumptions and the specific data of the analyzed IM. However, additional analyses (not included due to space limitations) indicate that variations in other influencing parameters, such as energy tariffs, discount rate, and equipment lifespan, can significantly alter TOC outcomes and, consequently, the preferred evaluation method. These findings highlight the importance of selecting an appropriate economic method to ensure accurate and reliable motor assessment.

Furthermore, industrial experience demonstrates that motor selection based solely on capital cost is inadequate. Practical considerations such as future energy price trends, after-sales service, availability and cost of spare parts, local technical support, brand reliability, and manufacturing origin play a critical role in informed investment decisions. The proposed framework and supporting software provide a practical and efficient tool for TOC assessment, enabling plant engineers to systematically compare different IM options. Future work will extend this approach to incorporate the combined effects of multiple economic factors, further enhancing decision-making accuracy in IM selection.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ayman Agha	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Khaled Alzaareer	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		
Hudefah Alkashashaneh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that no conflicts of interest are associated with this work.

INFORMED CONSENT

The authors confirm that all participants in this study informed consent.

ETHICAL APPROVAL

Not applicable. This study did not involve human participants or animals, and therefore ethical approval was not required in accordance with applicable national regulations and institutional guidelines.

DATA AVAILABILITY

The authors confirm that all data supporting the results of this study are fully accessible within the article and its supplementary materials.

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BIOGRAPHIES OF AUTHORS

Ayman Agha received his M.Sc., B.Sc. (Hon), and Ph.D. degrees in Electrical Power Engineering from the University of Science and Technology-AGH, Cracow, Poland, in 1989, 1997, respectively. He joined Jordan Phosphate Mines Co. (JPMC) in 1989 as a Maintenance Planner and Preventive Maintenance Engineer in the Projects Department, where he worked until 2000. From 2000 to 2004, he served as the Manager of the Studies and Design Department at Alfanar Co., Riyadh, KSA. In 2004, he returned to JPMC, worked on megaprojects. In 2014, he transitioned to academia, joining the Department of Electrical Engineering at Philadelphia University. Currently, he is an Associate Professor in Department of Renewable Energy at Arab Amman University, Amman, Jordan. He can be contacted at email: a.agha@aau.edu.jo.

Khaled Alzaareer received the B.Sc. and M.S. degrees in electrical power engineering from Yarmouk University, Irbid, Jordan, in 2010 and 2012, respectively, and the Ph.D. degree in electrical engineering from university of Quebec, Montreal, Canada in 2020. From 2017-2020, he was with the Power Electronics and Industrial Control Research Group (GREPCI), University of Quebec, Montreal, Canada. In 2020, he was a research assistant with Canada Excellence Research Chair in Smart, Sustainable and Resilient and Cities (CERC), Concordia University, Montreal, Canada. From 2020–2021, he joined Philadelphia University, Amman, Jordan, as an Assistant Professor. He is currently an Assistant Professor with Department of Energy Engineering, Al Hussien Technical University, Amman, Jordan. His research interests include power system operation, voltage stability and control, sensitivity analysis, integration of renewable energy resources, energy management, and smart grid. He can be contacted at email: Khalid.AlZareer@htu.edu.jo.

Hudefah Alkashashneh received an M.Sc. degree in Mechatronics Engineering from Philadelphia University, Jordan, in 2019 and a B.Sc. in Electrical Power and Control Engineering from the Jordan University of Science and Technology, Jordan, in 2012. He works as a teaching and research assistant at Al Hussein Technical University. From 2014 to 2025, he worked as a Laboratory Supervisor at the Department of Electrical Engineering at Philadelphia University. The following themes describe the researcher's interests: smart grids, renewable energy systems, power system stability, artificial intelligence, electrical machines, and the internet of things (IoT). He can be contacted at email: Huthaifa.Alkhashaneh@htu.edu.jo.