This is an Accepted Manuscript of an article published by Elsevier in Applied Energy, Vol. 240, on April 2019, available at: https://doi.org/10.1016/j.apenergy.2019.02.016

Techno-economic Optimal Power Rating of Induction Motors

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Abstract

Electric motors are valuable, long-life industrial assets, whose lifespan is often measured in decades. A period of unplanned motor downtime in an industrial plant frequently incurs an expenditure of thousands of euros per hour. As a consequence, plant engineers often focus their decisions on reliability rather than on operating cost (energy bill). Unfortunately, the high price of energy and its growing trend mean that operating cost has an increasingly negative impact on production cost and company competitiveness.

The problem of selecting the rated power of a line-operated single-speed electric motor to drive a time-variable mechanical load has traditionally been solved, based on the well-established root mean square (RMS) value of the time-power profile of the mechanical load. This conventional method of rating is strictly technical, since the rated power of the motor is determined, based only on the power profile of the load. No other factors are considered, such as the energy consumption throughout the whole in-service life of the motor, or, even better, the whole life cycle cost (LCC), which is defined as the net present value of purchasing, installing, operating (energy), maintaining and decommissioning the motor throughout its life. As a consequence, conventional rating often leads to the selection of motors with a power rating that is technically sufficient to drive the mechanical load, but insufficient to do so with the lowest possible energy (losses) consumption, or even better, with the lowest possible life cycle cost.

A new analytical method to determine the techno-economic optimum power rating of a line-operated single-speed electric motor to drive a time-variable mechanical load will be introduced in this paper. The proposed method takes into account not only the technical restrictions due to the time-power profile of the mechanical load, but also the whole life cycle cost. Based on the list of electric motors offered in the manufacturer's catalogue, the new methodology enables the optimum techno-economic rated power of the motor to be calculated, which minimizes the energy consumption (energy loss) throughout its in-service life or its total life cycle cost. The results show that the optimum techno-economic rating is one or two rated-power levels above the conventional rating based solely on the RMS load.

Keywords: Induction motors; Life cycle cost; Energy efficiency; CO_2 emissions; Power rating; Techno-economic optimization.

1. Introduction

Electric motors enjoy extensive applications as drivers of a large variety of equipment in industrial and service sectors, as well as in household electric appliances. With the recent irruption of electric motors in the power train of current electric vehicles, electric motors are now coming into their own with regard to road transport: one of the few fields of application that have been largely void of electric motors throughout the 20th century, and also a major contributor to carbon dioxide emissions worldwide.

Electric motor systems are responsible for approximately 70% of industrial electricity consumption and for about 35% of non-residential electricity (services) consumption in the European Union (EU) [1,2]. In 2015, final electricity consumption in the EU-28 reached 2743 TWh, mainly on account of three sectors: industry, the sector with the highest consumption with a share of 36.34% (997 TWh), followed by the services sector, representing 30.50% (837 TWh), and then the residential sector with 28.99% (795 TWh) [3]. This means an estimated electric motor consumption for the EU-28 of 698 TWh in industry and 293 TWh in the services sector in 2015: a total of 991 TWh (36.11%), which is practically equal to the consumption of the whole industry sector. Given that the EU-28 average value of carbon dioxide equivalent (CO_2eq) factor emissions was 374 thousand t(CO_2eq)/TWh [4], as a consequence of the energy consumed in these two sectors by electric motors, approximately 371 million tonnes of CO_2eq were emitted into the atmosphere in 2015.

The role of electric motors as major consumers of electricity in industry and service sectors has been largely recognized by policymakers all over the world [5]. As a result, almost all the main economies have implemented some kind of regulation regarding motor efficiency as a method for improving productivity/competitiveness (savings in operating cost) and meeting international commitments on climate change (emission reductions due to energy savings). For example, in the EU, electric motors (0.75 kW - 375 kW) lie within the scope of the Ecodesign Directive [6,7].

In 2015, according to Prodcom (EU statistics on the production of manufactured goods), 10,511,819 multi-phase AC motors (excluding traction motors) rated at 0.75 kW – 375 kW were sold in the EU-28 [8]. Within this power range, the market is clearly dominated by three-phase AC induction motors, representing around 85% of the market share [9,10].

Issues related to energy consumption by electric motors and their related CO_2 emissions have also been broadly discussed by researchers involving a wide variety of perspectives and publications: industry applications [11,12], energy saving [13,14], the convenience of using high-efficiency motors to replace standard motors [15], minimum efficiency performance standard [16], partial load [17] and oversizing [18,19], energy efficiency standards [20,21] and policies [22,23], the influence of voltage unbalance [24,25] and derating [26], harmonics [27] and other power quality issues [28], the convenience of rewinding or replacing failed motors [29], CO_2 emissions [30,31], the variation in losses and efficiency under variable speed and load conditions [32,33], energy conservation [34,35] and others [36,37]. Naturally, electromobility applications (electric vehicles) are also receiving major attention from the research community form the point of view of energy management [38-40], regenerative braking [41,42], the use of batteries and ultracapacitors as energy storage devices [43], and others [44,45].

Focusing on the aspects more directly related to the rated power of induction motors and its energy efficiency class, in 1999, Akbaba [34] analysed the potential of energy conservation in industry by using energy-efficient electric motors compared with those of standard efficiency motors. Ferreira, Cisneros-González and de Almeida pointed out in [19] that most industrial three-phase squirrel-cage induction motors are oversized mainly due to the use of safety factors associated with uncertainty about mechanical load requirements, conservative design rules, and the discrete availability of commercial rated power. In that work, the authors analysed the potential benefits and drawbacks of motor oversizing. Da Costa Bortoni [18] also agrees that the oversizing practice is more a problem related to the deficiency of proper information than a lack of "best practices". The author warns that figuring out whether a motor is truly oversized is not a simple task and presents a road map to properly evaluate whether a direct line-fed three-phase induction motor is oversized.

The problem of selecting the rated power of a line-operated single-speed electric motor to drive a time-variable mechanical load has been solved traditionally, based on the well-established RMS value of the time-power profile of the mechanical load. Since 1939, when L.E. Hildebrand published his paper "Duty cycles and motor rating" [46], the RMS method was fully accepted by the technical community and has been found in technical texts and teaching handbooks since then up to the present [47]. Nevertheless, this conventional method fully disregards all the aspects related to energy consumption, efficiency or operating (energy) cost, which precisely constitutes the greatest part of the total LCC.

Although electric motors remain the subject of extensive research work, the influence of the selection of the optimum motor to drive a certain mechanical load is a subject rarely considered. But this is certainly an issue worth analysing, since the decision regarding the choice of a particular electric motor to drive a mechanical load determines the losses of the motor load system and thus its energy consumption, operating cost and associated CO_2 emissions.

In order to make an informed decision on the investment of any industrial equipment, such as the selection of a motor, it is essential to evaluate the initial investment (purchase, installation and commissioning cost), the net present value of the operating cost (energy and maintenance) throughout the whole in-service life of the motor, and the decommissioning cost (conditioning or removal cost and the residual value, which is the motor resale or scrap value) at the end of the expected life of the said motor. Decision-making based on the lowest LCC, although often recommended [48,10], has yet to become common engineering practice. This minimum LCC approach offers engineers a broader view of what can be expected from their decisions. This evaluation involves attaining reliable information on the mechanical load and on the electric motors for comparison in order to estimate the operating conditions and the energy and maintenance cost, while also taking into account the time value (depreciation) of money and potential annual energy cost increases. It is much more common to perform a simple payback period analysis which compares the total cost of investment to annual operating savings.

Unfortunately, there is no method available for the calculation of the rated power value of a motor based on the lowest LCC, since the motor must be chosen by evaluation. To address this gap, a new analytical methodology to determine the optimum power rating of a single-speed electric motor to drive a time-variable mechanical load will be introduced in this paper. The proposed methodology takes into account not only the technical restrictions, due to the power profile of the mechanical load, but also either the energy consumption throughout the whole life of the motor or the net present value of purchasing, installing, commissioning, operating (energy), maintaining and disposing of the motor over its life cycle. Based on the list of electric motors offered in the catalogue of a manufacturer, the new methodology enables the calculation of the optimum techno-economic rated power of the motor which minimizes either the energy consumption (energy loss) throughout its in-service life or its total LCC. Therefore, the proposal constitutes a clear advance with respect to the state of the art because the trial-and-error procedures are surpassed. The proposed methodology is able to directly compute, in an analytical way, the motor rated power by minimizing the selected objective function for given loading conditions.

As can be observed, the techno-economic approach of the proposed rating method is much more comprehensive than the conventional and well-established method of the RMS value of the load (which completely ignores energy cost) and could be seen as an extension or an evolution of the conventional method, which is already able to integrate (by taking into account) both the technical restrictions imposed by the mechanical load and the operating (energy) cost throughout the whole in-service life of the motor.

After this introduction, the remainder of the paper is organized as follows. The conventional method of determining the rated power of a motor is reviewed in Section 2, with its main weaknesses explained. Section 3 presents the theory of the proposed method, including analytical expressions for optimum rated power, for minimum energy (losses) and for the minimum LCC. The main results of a case study are presented and briefly discussed in Section 4, where the advantages of the proposed optimization method in terms of energy and cost savings are also be shown. A sensitivity analysis to demonstrate the robustness of the solutions is included in this section. Finally, Section 5 summarizes the main findings of the work. A list price of IE2 and IE3 metric motors from a worldwide electric motor manufacturer has been included in the Appendix.

2. Selecting the Rating Power of a Motor

The problem of selecting the rated power of a line-operated single-speed electric motor to drive a time-variable mechanical load, $P(t)$, has traditionally been solved, based on the well-established RMS value of the time-power profile of the mechanical load [47,48]. Accordingly, a motor, with rated power (continuous running duty S1), P_R, equal to or above the RMS value of the mechanical load power profile, P_{RMS}, is selected from among those available, P_{Ri}, in the catalogue of the manufacturer ($P_R = \min(P_{Ri}) \geq P_{RMS}$), while observing peak load restrictions. This well-established approach is mainly focused on two ideas:

- Maintenance of the temperature of the windings below their maximum allowable limit, thereby preventing a premature thermal failure which could shorten the expected in-service life of the motor.
- Minimization of the purchase (and installation) cost of the motor.

It should be borne in mind, however, that any motor with power rated over the RMS value of the power profile operates with a temperature below the maximum permitted by the insulation, and will have a longer in-service life than expected, since it has become less prone to failure. The selection of the motor with the lowest rated power compatible with the mechanical load profile in fact only guarantees the minimum purchase cost. Nevertheless, the purchase cost used to be a very small proportion (less than 5-10%) of the LCC of the motor, since the cost of energy forms the greatest part of the total cost [49-51]. As a consequence, conventional rating is nowadays questioned, mainly due to the fact that it completely disregards the cost of energy, which constitutes the greatest part of the total present cost.

3. Materials and Methods

The problem of determining the techno-economic optimum rated power of a line-operated single-speed cage induction motor for driving a specified time-variable mechanical load (at an early project stage) is addressed in this work. Although the use of power converters is becoming popular, line-operated motors are still the most common solution for driving industrial loads.

Based on the list price and the technical data of electric motors offered in the catalogue of a manufacturer, the new method enables the analytical determination of not only the rated power of the motor, which minimizes energy consumption (energy loss) throughout its in-service life, but also its total LCC.

The basic input data can be classified into three main categories:

- Mechanical load. It is necessary to ascertain the (expected) time-power profile of the mechanical load, $P(t)$, throughout the yearly operating time, T.
- Motor. The list price and the technical data from a manufacturer's catalogue are required. All of the motors should possess the same general characteristics: speed (number of poles), voltage, frequency, efficiency class, insulation class.
- Economic data. The price of the electric energy and its expected yearly rate of growth are required, as are the discount rate and the estimated in-service life of the motor.

The required information is presented in greater detail in the following sections.

3.1 Power losses

Table 1 summarizes the efficiency data of low-voltage, four-pole, general-performance, cast-iron motors from a multinational manufacturer, for the IE3 and IE2 efficiency classes [52]. As can be observed, although efficiency at the 100% (full) load level is the only value of rated efficiency that must be determined according to the IEC 60034-2-1 [53], most manufacturers also include motor efficiency at the 75% and 50% load level in their catalogues (see Appendix).

The efficiency data given in the manufacturer's catalogue enable a model of power losses, $P_L(P_R, P_{pu} = P/P_R)$, to be extracted for every motor in that catalogue. For each rated power, P_R, and normalized or relative power load, P_{pu}, the efficiency data, $\eta(P_R, P_{pu})$, allow the power losses to be calculated corresponding to each relative power load:

$$P_L(P_R, P_{pu} = P/P_R) = \frac{P_{pu} \cdot P_R}{\eta(P_R, P_{pu})} - P_{pu} \cdot P_R = P_{pu} \cdot P_R \left(\frac{1}{\eta(P_R, P_{pu})} - 1 \right) \tag{1}$$

In this work, a simplified quadratic binomial model of power losses, $P_L(P_R, P_{pu})$, has been considered. This quadratic binomial power-loss model has two terms:

- Constant losses, k_{LF}. This term describes the constant or fixed no-load power losses, independent of the motor load. This term basically corresponds to the sum of the iron losses and friction and windage losses.
- Variable losses, $k_{LV} \cdot P^2_{pu}$. This second term describes the variation in the load-dependent losses with the square of the normalized or relative power load, P_{pu}.

This term largely corresponds to the Joule effect in the (stator and rotor) conductors.

$$P_L(P_R, P_{pu} = P/P_R) = k_{LF} + k_{LV}\frac{P^2}{P_R^2} = k_{LF} + k_{LV}P_{pu}^2 \qquad (2)$$

Table 1. Cage induction motors (CENELEC-design): efficiency data of general-performance cast-iron motors designed for low voltage (440 V, 50 Hz), four poles, IP 55, IC 411, and insulation class F (temperature rise class B) [52].

Output kW	**IE3 (premium efficiency)**			**IE2 (high efficiency)**		
	Full load 100% *	3/4 load 75%	1/2 load 50%	Full load 100% *	3/4 load 75%	1/2 load 50%
0.25	73.5	70.1	63.8	67.0	63.1	56.6
0.37	77.3	74.9	69.8	69.5	69.0	64.4
0.55	80.8	80.7	78.0	73.5	73.2	69.2
0.75	82.5	81.2	77.6	79.6	78.5	74.4
1.1	84.1	83.4	80.9	81.4	80.7	77.2
1.5	85.3	84.4	82.1	82.8	82.6	79.8
2.2	86.7	86.1	84.1	84.3	84.2	81.9
3	87.7	87.7	86.5	85.5	85.4	83.3
4	88.6	88.9	88.1	86.6	86.2	84.6
5.5	89.6	90.4	90.2	87.7	87.5	86.2
7.5	90.4	90.7	90.3	88.7	88.6	87.5
11	91.4	91.8	91.1	89.8	89.9	89.2
15	92.1	92.4	91.6	90.6	91.1	90.5
18.5	92.6	93.2	92.9	91.2	91.5	90.6
22	93.0	93.5	93.3	91.6	91.3	90.2
30	93.6	93.8	93.4	92.3	92.4	92.0
37	93.9	94.1	93.8	92.7	92.7	92.2
45	94.2	94.4	94.0	93.1	93.0	92.3
55	94.6	94.7	94.0	93.5	93.4	92.7
75	95.0	95.2	94.8	94.2	94.2	93.5
90	95.2	95.3	94.8	94.4	94.6	94.1
110	95.4	95.4	94.8	94.7	94.6	93.8
132	95.6	95.8	95.3	95.0	95.0	94.3
160	95.8	96.0	95.8	95.2	95.3	94.6
200	96.0	96.4	96.4	95.3	95.4	94.9
250	96.0	96.0	95.6	95.2	95.2	94.4
315	96.0	96.0	95.6	95.5	95.5	94.8
355	96.0	96.2	95.8	95.5	95.7	95.2

* Efficiency according to IEC 60034-30-1; 2014 [54]

This quadratic binomial power-loss model is similar to that proposed in IEC/TS 60034-31 [50], which is based on the intermediate results or constants v_0 and v_L, calculated from the efficiency at the full load and 3/4 load levels. A similar matrix model of power losses, based on three known values of efficiency corresponding to three reference relative loads (100%, 75% and 50%), was also used in [19].

For each motor, the values of the two constants of the model of losses, k_{LF} and k_{LV}, can be identified from the lineal regression of the data on power losses versus the squared normalized power in Table 1. Table 2 shows the value of the constants of the model of losses identified by linear regression of the power-loss data, which are determined by (1) from the manufacturer’s efficiency data.

Table 2. Coefficients of the binomial power-loss model, $P_L(P_R,P_{pu}) = k_{LF} + k_{LV}\cdot P^2_{pu}$, for IE3 and IE2 cage induction motors in Table 1.

	IE3 (premium efficiency)				**IE2 (high efficiency)**			
Rated power	Coefficients		Goodness of fit		Coefficients		Goodness of fit	
P_R (kW)	k_{LF} (kW)	k_{LV} (kW)	Determination coefficient R^2	Correlation coefficient	k_{LF} (kW)	k_{LV} (kW)	Determination coefficient R^2	Correlation coefficient
0.25	0.0650	0.0255	0.9961	0.9980	0.0878	0.0360	0.9895	0.9947
0.37	0.0709	0.0380	0.9983	0.9991	0.0811	0.0805	0.9975	0.9988
0.55	0.0594	0.0710	0.9995	0.9997	0.0958	0.1016	0.9980	0.9990
0.75	0.0916	0.0677	0.9997	0.9998	0.1074	0.0844	0.9995	0.9997
1.1	0.1046	0.1039	0.9993	0.9996	0.1319	0.1189	0.9992	0.9996
1.5	0.1339	0.1259	0.9966	0.9983	0.1478	0.1629	0.9989	0.9994
2.2	0.1667	0.1720	0.9985	0.9992	0.1863	0.2226	0.9996	0.9998
3.0	0.1734	0.2483	0.9995	0.9997	0.2302	0.2778	0.9998	0.9999
4.0	0.1897	0.3257	0.9999	0.9999	0.2833	0.3384	0.9980	0.9990
5.5	0.1846	0.4531	0.9999	1.0000	0.3345	0.4399	0.9985	0.9993
7.5	0.2758	0.5234	0.9992	0.9996	0.4013	0.5577	0.9987	0.9994
11.0	0.3681	0.6647	0.9997	0.9998	0.4789	0.7754	0.9988	0.9994
15.0	0.4831	0.8003	0.9995	0.9997	0.5273	1.0266	0.9998	0.9999
18.5	0.4430	1.0310	0.9994	0.9997	0.6784	1.1027	0.9996	0.9998
22.0	0.4997	1.1552	1.0000	1.0000	0.9356	1.0914	0.9977	0.9988
30.0	0.7355	1.3197	0.9997	0.9999	0.9247	1.5909	0.9980	0.9990
37.0	0.8398	1.5707	0.9994	0.9997	1.1401	1.7896	0.9975	0.9988
45.0	0.9955	1.7779	0.9999	1.0000	1.4145	1.9359	0.9981	0.9990
55.0	1.2840	1.8491	0.9996	0.9998	1.6376	2.2020	0.9984	0.9992
75.0	1.4232	2.5218	1.0000	1.0000	1.9445	2.6785	0.9999	0.9999
90.0	1.7778	2.7595	1.0000	1.0000	1.9750	3.3592	0.9999	1.0000
110	2.2579	3.0483	1.0000	1.0000	2.8050	3.3577	0.9999	0.9999
132	2.2770	3.7736	0.9987	0.9993	2.9986	3.9456	1.0000	1.0000
160	2.3514	4.6718	0.9999	0.9999	3.3545	4.6832	0.9988	0.9994
200	2.1808	6.1390	0.9999	0.9999	3.8725	5.9878	1.0000	1.0000
250	4.2477	6.2010	0.9992	0.9996	5.6330	6.9379	0.9993	0.9996
315	5.3521	7.8132	0.9992	0.9996	6.5326	8.2851	0.9997	0.9999
355	5.3670	9.3737	0.9991	0.9995	6.2609	10.4043	0.9989	0.9994

Finally, Figure 1 shows the point clouds of the fixed-loss constants (P_R, $k_{LF}(P_R)$) and variable-loss constants (P_R, $k_{LV}(P_R)$) in Table 2 as functions of the rated power of each of the motors. This figure also shows the respective linear regression lines of each of these constants with the rated power of the motors.

For IE3 motors, the linear regression fitting results in:

$$k_{LF}(P_R) \approx k_{LFF} + k_{LFV}\cdot P_R = 0.1735 + 0.0152\cdot P_R \quad (R^2 = 0.9712)$$

$$k_{LV}(P_R) \approx k_{LVF} + k_{LVV}\cdot P_R = 0.3253 + 0.0254\cdot P_R \quad (R^2 = 0.9878)$$

Using (2), the power-loss model yields:

$$P_L(P_R, P_{pu} = P/P_R) = k_{LF} + k_{LV}\cdot P_{pu}^2 = k_{LFF} + k_{LFV}\cdot P_R + (k_{LVF} + k_{LVV}\cdot P_R)\cdot P_{pu}^2 \qquad (3)$$

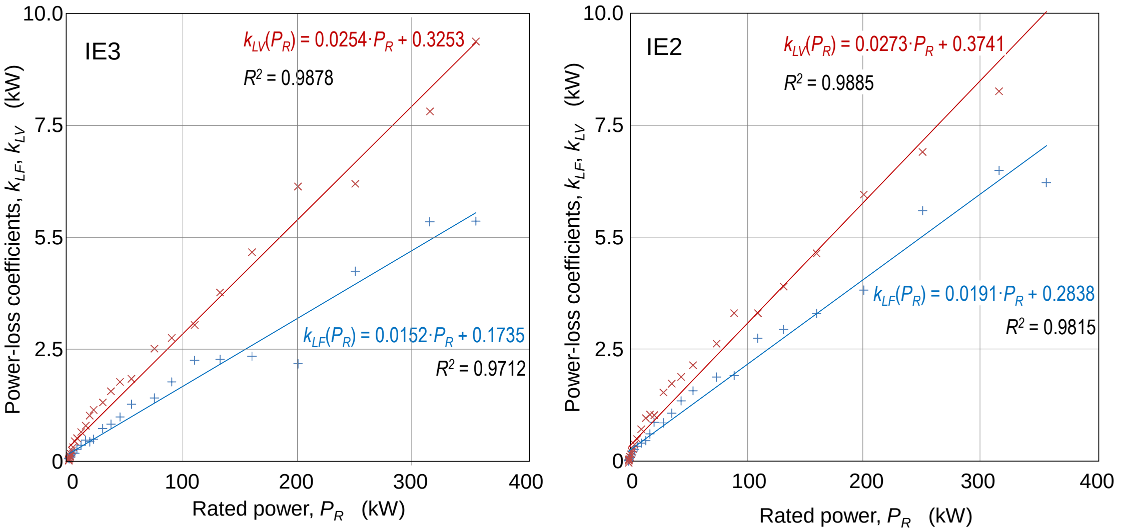

Figure 1. Point clouds and lines of linear regression corresponding to the fixed-loss constants (P_R, $k_{LF}(P_R)$) and variable-loss constants (P_R, $k_{LV}(P_R)$) as functions of the rated power for the IE3 and IE2 cage induction motors in Table 1.

For IE3 motors, the linear regression fitting results in:

$$k_{LF}(P_R) \approx k_{LFF} + k_{LFV} \cdot P_R = 0.1735 + 0.0152 \cdot P_R \quad (R^2 = 0.9712)$$

$$k_{LV}(P_R) \approx k_{LVF} + k_{LVV} \cdot P_R = 0.3253 + 0.0254 \cdot P_R \quad (R^2 = 0.9878)$$

Using (2), the power-loss model yields:

$$P_L(P_R, P_{pu} = P / P_R) = k_{LF} + k_{LV} \cdot P_{pu}^2 = k_{LFF} + k_{LFV} \cdot P_R + (k_{LVF} + k_{LVV} \cdot P_R) \cdot P_{pu}^2 \tag{3}$$

For IE2 motors, the coefficients of the power-loss model yield:

$$k_{LF}(P_R) \approx k_{LFF} + k_{LFV} \cdot P_R = 0.2838 + 0.0191 \cdot P_R \quad (R^2 = 0.9815)$$

$$k_{LV}(P_R) \approx k_{LVF} + k_{LVV} \cdot P_R = 0.3741 + 0.0237 \cdot P_R \quad (R^2 = 0.9885)$$

3.1.1 A first approach to the optimum power rating for minimum power losses

By using the coefficients of the binomial power-loss model, Figure 2 shows the variation in power losses with the power load for five IE3 motors rated 22 kW, 30 kW, 37 kW, 45 kW and 55 kW.

As can be observed, as the power load grows, the curves of losses cut off, two by two, at points $P_{22\text{-}30}$ (15.98, 1.11), $P_{30\text{-}37}$ (18.01, 1.27), $P_{37\text{-}45}$ (24.08, 1.51) and $P_{45\text{-}55}$ (32.87, 1.94). These four intersection points allow for the definition of five power-load intervals, relative to the losses:

- For a power load lower than that corresponding to the first crossing point, $P_{22\text{-}30}$ ($P \leq 15.98$ kW), the minimum power losses correspond to the motor rated 22 kW.
- For a power load between the points $P_{22\text{-}30}$ and $P_{30\text{-}37}$ (15.98 kW $< P \leq 18.01$ kW), the minimum power losses correspond to the motor rated 30 kW.
- For a power load between the points $P_{22\text{-}37}$ and $P_{37\text{-}45}$ (18.01 kW $< P \leq 24.08$ kW), the minimum power losses correspond to the motor rated 37 kW.

- For a power load between the points $P_{37\text{-}45}$ and $P_{45\text{-}55}$ (24.08 kW $< P \leq 32.87$ kW), the minimum power losses correspond to the motor rated 45 kW.
- For a power load above that corresponding to the last crossing point $P_{45\text{-}55}$ (32.87 kW $< P \leq 55$ kW), the minimum power losses correspond to the motor rated 55 kW.

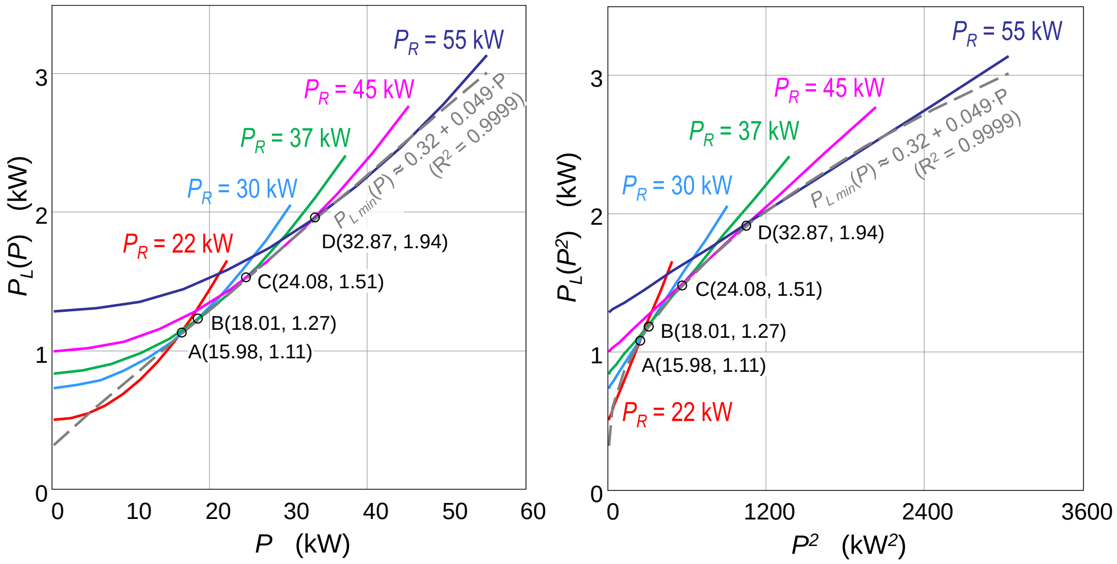

Figure 2. Variation in the power losses with the power load (left) and with the square of the power load (right) for five IE3 motors rated 22 kW, 30 kW, 37 kW, 45 kW and 55 kW.

This suggests that, for each level of constant mechanical power load, P_M:

- First, there is a motor in the manufacturer's catalogue with a rated power, $P_{R\,PLmin}$, which can drive the mechanical load with the minimum power (or energy) losses, $\min(P_L(P_M, P_R))$, and without overload ($\exists P_{R\,PLmin} > P_M$).
- Second, the rated power of the motor with minimum power (or energy) losses, $P_{R\ PLmin}$, is always higher than the mechanical power load ($\exists P_{R\ PLmin} > P_M$), because the crossing point between contiguous motors occurs before reaching the rated power of the smaller motor.
- Third, the rated power of the motor with the minimum LCC, $P_{R\,LCCmin}$, is always higher than the mechanical power load, P_M, and lower than or equal to the rated power for minimum power losses, $P_{R\,LCCmin}$, since the purchase cost exerts a downward pressure on the rated power for the minimum LCC ($\exists P_{R\ LCCmin}$; $P_M < P_{R\,LCCmin} \leq P_{R\,PLmin}$).

For example, to drive a constant mechanical load, P = 22 kW (located between points $P_{30\text{-}37}$ and $P_{37\text{-}45}$), any of the five motors considered could be used without any risk of overload. Each of these motors should operate with a certain amount of power losses, but only for one of the motors would these losses be the smallest. In the case where the 22 kW rated power motor were to be used, it would work with power losses equal to $P_L(P_R = 22$ kW, $P_{pu} = 22/22) = 2$ kW. However, if the motor rated 37 kW were employed to drive the load, it would work with lower power losses, $P_L(P_N = 37$ kW, $P_{pu} = 22/37) = 1.44$ kW < 2 kW $= P_L(P_R = 22$ kW, $P_{pu} = 1)$. Therefore, although the initial purchase and installation cost of the motor rated 37 kW is higher than that corresponding to the motor rated 22 kW, it could drive the 22 kW mechanical load with a lower energy demand and, consequently, with lower operating costs (energy bill).

Consequently, in order to drive a given time-constant mechanical load (continuous running duty S1), $P(t) = P$, there must exist two motors in the manufacturer's catalogue with rated powers $P_{R\text{-}PLmin}$ and $P_{R\text{-}LCCmin}$, which are both larger than the driven load ($P < P_{R\text{-}LCCmin} < P_{R\text{-}PLmin}$), and which would work with:

- Minimal power (energy) losses. There must be a motor with an optimum rated power, $P_{R\text{-}PLmin}$, which verifies that $P_L(P_{R\text{-}PLmin}, P_{pu} = P/P_{R\text{-}PLmin}) < P_L(P_R = P, P_{pu} = 1$ pu). Since the mechanical power (energy) supplied to the driven mechanical load, P, does not depend on the rated power of the motor used to drive it, this minimum power-loss criterion is equivalent to the minimum demand of electrical power (energy).
- Minimum overall LCC (purchase + present value of energy). There must be a motor with an optimum rated power, $P_{R\text{-}LCCmin}$, which minimizes the overall LCC, or, equivalently, a motor which verifies that the sum of the initial investment required for its acquisition and commissioning, $I(P_{R\text{-}LCCmin})$, plus the present value of its overall operating costs over its in-service LCC, $_{P\text{-}E}(P_R = P_{R\text{-}LCCmin}, P_{pu} = P/P_{R\text{-}LCCmin})$, must be at the minimum level.

In Figure 3, it can also be observed that the points of intersection of the power-loss curves, $P_{22\text{-}30}$ (15.98, 1.11), $P_{30\text{-}37}$ (18.01, 1.27), $P_{37\text{-}45}$ (24.959, 1.650) and $P_{45\text{-}55}$ (30.118, 1.980), which are the points that limit the intervals of load power, in which each motor displays the minimum losses, are almost aligned in a straight line. Hence, the successive intersection points of the power-loss curves should be well represented by fitting a linear regression line of the form:

$$P_{L\,min}(P_{R\,PLmin}, P) \approx k_{L0\,PLmin} + k_{L1\,PLmin} \cdot P$$

for the five motors considered:

$$P_{L\,min}(P_{R\,PLmin}, P) = 0.32 + 0.049 \cdot P \quad (R^2 = 0.9999) \tag{4}$$

This line of minimum power losses should enable the swift determination of the optimum rated power of the motor as well as providing a good estimation of the losses, once either the equivalent constant (continuous running duty S1) load or the characteristic load (RMS value of the variable mechanical load) is known.

3.2 Purchase cost

Figure 3 shows the variation in the rated power of the purchase price, $C_P(P_R)$, and the specific purchase price, $C_S(P_R) = C_P(P_R)/P_R$, for the cage induction motors of IE3 and IE2 efficiency classes, as given in Table 1 (see Table A.1 in Appendix A) [55].

As can be observed, the point clouds of purchase prices as functions of the rated power of the IE3 and IE2 motors, (P_R, $C_P(P_R)$), are very well fitted by their respective linear regression lines. Accordingly, the purchase price for IE3 motors can be approximated as:

$$C_P = C_P(P_R) \approx c_{PF} + c_{PV} \cdot P_R = 306.74 + 97.079 \cdot P_R \quad (R^2 = 0.9994)$$

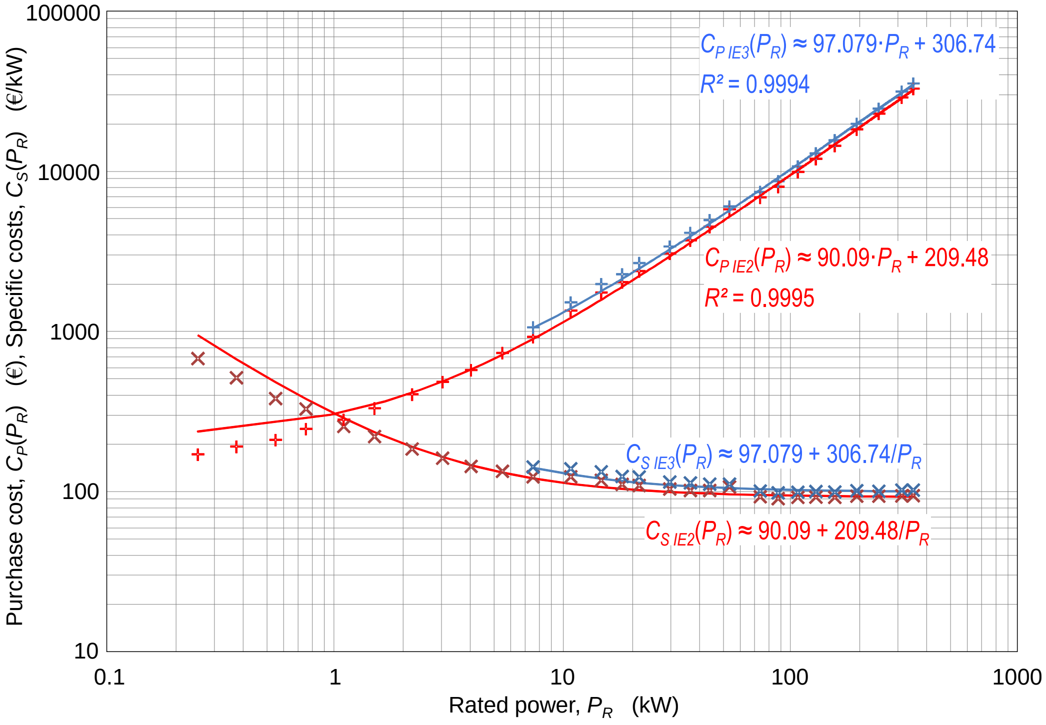

Figure 3. Variation in the rated power of the purchase cost (list price), $C_P(P_R)$, and the specific purchase price, $C_S(P_R) = C_P(P_R)/P_R$, for induction motors designed for low voltage, four poles, and IE3 and IE2 efficiency classes in Table 1.

and, for IE2 motors, as:

$$C_P = C_P(P_R) \approx c_{PF} + c_{PV} \cdot P_R = 209.48 + 90.090 \cdot P_R \quad (R^2 = 0.9995)$$

Qualified customers, according to their volume of purchase, can often profit from discounts of up to 80% on the list price. The initial cost, $I(P_R)$, in addition to the true purchase cost, $(1 - k_d) \cdot C_P$, with the proper discount factor, k_d, should also include all the installation and conditioning costs, such as the cost of command, starting and protection devices or the capacitor bank for power factor compensation [19,56,57]. All these auxiliary costs can be considered proportional to the purchase price of the motor, $C_A = k_A \cdot C_P$. As a result, a linear initial cost has been considered in the form of:

$$I(P_R) \approx (1 - k_d + k_A) \cdot C_P(P_R) = (1 - k_d + k_A) \cdot (c_{PF} + c_{PV} \cdot P_R) = c_F + c_V \cdot P_R, \tag{5}$$

where the new constants are:

$$c_F = (1 - k_d + k_A) \cdot c_{PF}$$

$$c_V = (1 - k_d + k_A) \cdot c_{PV}$$

3.3 Optimum rated power for minimum energy and losses

The annual energy, $E(P_R, P(t))$, consumed by an electric motor driving a mechanical load with a time-power profile, $P(t)$, during T operational hours a year, is composed of two terms: the mechanical energy delivered to the driven mechanical load (which is independent of the motor rated power), $E_M(P(t))$, and the power losses in the motor, $E_L(P_R, P(t))$. Accordingly, the total electric energy, E_T, consumed throughout the N years of expected in-service life of the electric motor can be expressed as:

$$E_T(P_R, P(t)) = \sum_{n=1}^{N} E(P_R, P(t)) = N \cdot E(P_R, P(t)) = N \cdot \left(E_M(P(t)) + E_L(P_R, P(t)) \right)$$

The yearly amount of electrical energy absorbed corresponding to the mechanical energy supplied to the driven load can be expressed as:

$$E_M(P(t)) = \int_0^T P(t)dt = T \frac{1}{T} \int_0^T P(t)dt = T \cdot P_m$$

where the average power is:

$$P_m = \frac{1}{T} \int_0^T P(t)dt$$

It can be observed that:

- The mechanical energy supplied to the driven load, E_M, depends only on the time-load profile of the driven mechanical load, $P(t)$, but does not depend on the motor chosen to drive it. That is, whatever its rated power, the chosen motor must deliver the specified power profile or energy annually.
- For the purpose of calculating the annual mechanical energy supplied, all the necessary information of the time-load profile is summarized in the value of its average power, P_m, in the annual operating time, T.

On the other hand, the power-loss model, $P_L(P_R, P(t))$, leads to the formulation of an expression for the loss of energy during the first year of operation of the (chosen) motor, $E_L(P_R, P(t))$, written as:

$$\begin{aligned} E_L(P_R, P(t)) &= \int_0^T P_L(P_L, P(t))dt \approx \int_0^T \left(k_{LF} + k_{LV} \cdot \frac{P^2(t)}{P_R^2} \right) dt \\ &= T \cdot k_{LF} + T \cdot \frac{k_{LV}}{P_R^2} \frac{1}{T} \int_0^T P^2(t)dt = T \cdot \left(k_{LF} + k_{LV} \cdot \frac{P_{RMS}^2}{P_R^2} \right) \end{aligned}$$

where the RMS power is:

$$P_{RMS} = \sqrt{\frac{1}{T} \int_0^T P^2(t)dt}$$

Again, it is noteworthy that:

- The yearly energy loss, E_L, depends both on the time-load profile of the driven mechanical load, $P(t)$, and on the rated power of the motor chosen to drive it, P_R.
- For the purpose of calculating the annual energy loss with the model of power losses used, all the necessary information from the time-load profile is summarized by its RMS value, P_{RMS}.

Now, taking into account the power-loss model (3), the annual energy loss can be approximated as a function of the load profile of the driven mechanical load, $P(t)$, and the rated power of the chosen motor, P_R:

$$E_L(P_R, P(t)) = \int_0^T P_L(P_R, P(t))dt \approx \int_0^T \left(k_{LF}(P_R) + k_{LV}(P_R) \cdot \frac{P^2(t)}{P_R^2} \right) dt$$

$$= T \cdot \left(k_{LF}(P_R) + k_{LV}(P_R) \cdot \frac{P_{RMS}^2}{P_R^2} \right) = T \cdot \left(k_{LFF} + k_{LFV} \cdot P_R + (k_{LVF} + k_{LVV} \cdot P_R) \cdot \frac{P_{RMS}^2}{P_R^2} \right)$$

The total amount of electric energy consumed yearly can now be expressed as the sum of the mechanical energy and the energy loss:

$$E(P_R, P(t)) = E_M(P(t)) + E_L(P_R, P(t)) = \int_0^T P(t)dt + \int_0^T P_L(P_R, P(t))dt$$

$$\approx T \cdot \left(P_m + k_{LFF} + k_{LFV} \cdot P_R + (k_{LVF} + k_{LVV} \cdot P_R) \cdot \frac{P_{RMS}^2}{P_R^2} \right)$$

The total amount of energy throughout the whole life cycle of the motor, E_T, can be obtained by multiplying the annual energy by the number of years of expected life of the motor, N:

$$E_T(P_R, P(t)) = \sum_{n=1}^{N} E(P_R, P(t)) = N \cdot E(P_R, P(t)) = N \cdot \left(E_M(P(t)) + E_L(P_R, P(t)) \right)$$

$$\approx N \cdot T \cdot \left(P_m + k_{LFF} + k_{LFV} \cdot P_R + (k_{LVF} + k_{LVV} \cdot P_R) \cdot \frac{P_{RMS}^2}{P_R^2} \right)$$

This expression shows the total electric energy as a function of the rated power of the motor, P_R, and of two magnitudes related to the load profile: P_m and P_{RMS}. Therefore, the optimum rated power of the motor, which minimizes the total electrical energy (or the total energy loss) consumed during the whole in-service life of the motor, can be obtained by cancelling out the partial derivative of the total electric energy absorbed (or energy loss), with respect to the rated power of the motor, resulting in:

$$\frac{\partial E_T(P_R, P(t))}{\partial P_R} = \frac{N \cdot \partial E_L(P_R, P(t))}{\partial P_R} \approx -\left(k_{LFV} - \left(\frac{2k_{LVF} \cdot P_R}{P_R^4} + \frac{k_{LVV}}{P_R^2} \right) \cdot P_{RMS}^2 \right) \cdot N \cdot T = 0$$

The condition of minimum consumed energy or minimum energy loss can also be written as:

$$P_R^3 - \frac{k_{LVV} \cdot P_{RMS}^2}{k_{LFV}} \cdot P_R - \frac{2k_{LVF} \cdot P_{RMS}^2}{k_{LFV}} = 0$$

This cubic expression can be solved using Cardano's method. Accordingly, the optimum rated power of the motor results in:

$$P_{R\,ETmin} = P_{R\,ELmin} = \sqrt[3]{\frac{k_{LVF} \cdot P_{RMS}^2}{k_{LFV}} + \sqrt{\Delta}} + \sqrt[3]{\frac{k_{LVF} \cdot P_{RMS}^2}{k_{LFV}} - \sqrt{\Delta}}$$

where the discriminant, Δ, is:

$$\Delta = \left(\frac{k_{LVF} \cdot P_{RMS}^2}{k_{LFV}} \right)^2 - \left(\frac{k_{LVV} \cdot P_{RMS}^2}{3 \cdot k_{LFV}} \right)^3$$

This approach is focused only on the energy or the energy loss, and the cost of the energy, which is the greater part of the total cost of the motor throughout its whole in-service life. However, this selection method ignores the initial cost of the motor.

3.4 Optimum rated power for minimum life cycle cost

In order to calculate the LCC of a motor which must drive a mechanical load with a time-load profile, $P(t)$, it is necessary to consider the present or actual value of each of the costs involved in its operation throughout its expected life. If the initial investment or acquisition and commissioning cost of a motor with a rated power, P_R, is $I(P_R)$, and it has a present or actual operating cost, $C_{PO}(P_R,P(t))$, a decommissioning cost, $C_D(P_R)$, and a residual value, $V_R(P_R)$, its LCC, $LCC(P_R,P(t))$, can be expressed as:

$$LCC(P_R, P(t)) = -I(P_R) - C_{PO}(P_R, P(t)) - C_D(P_R) + V_R(P_R)$$

Induction motors are often repaired along their lifetime (bearing replacement and/or stator rewinding) [58,59], which leads to a repair cost and a reduction in efficiency in the range of 1.0%-2.5% [50]. Even the cost of unplanned motor downtime could be included in this expression. For the sake of simplicity, these issues have not been considered here.

In this work, it has been considered that the operating cost corresponds mainly to the cost of the energy, $C_{PO}(P_R,P(t)) = C_{PET}(P_R,P(t))$. However, an ordinary maintenance cost or the cost of the contracted peak power could also be included in this term, although this has not been included here.

It should be noted that the first three terms of the LCC are negative, since they correspond to expenses, while only the latter is positive, since it represents the income resulting from the sale of the motor (and its auxiliary elements) as second-hand equipment or for the recycling of its materials.

In this work, it is assumed that both the present cost of decommissioning and the present residual value of the motor depend on the rated power of the motor. More precisely, we considered that both these amounts are proportional to the purchase cost of the motor:

$$C_D(P_R) = k_D \cdot C_P(P_R)$$

$$V_R(P_R) = k_R \cdot C_P(P_R)$$

In this way, the LCC, using (5), results in:

$$\begin{aligned} LCC(P_R, P(t)) &= -I(P_R) - C_{PO}(P_R, P(t)) - C_D(P_R) + V_R(P_R) \\ &\approx -(1 - k_d + k_A + k_D - k_R) \cdot C_P(P_R) - C_{PO}(P_R, P(t)) = k_{EQ} \cdot C_P(P_R) - C_{PO}(P_R, P(t)) \end{aligned}$$

where the new constant is:

$$k_{EQ} = 1 - k_d + k_A + k_D - k_R$$

Finally, it is necessary to calculate the present or actual value of the operating cost over the expected life cycle of the motor. To this end, it is necessary to calculate the annual amount of electrical energy absorbed (the sum of the mechanical energy that must be supplied to the mechanical load and the losses of the motor), its cost, and the accumulated present or actual value throughout the whole in-service life of the motor.

The cost of the electrical energy corresponding to the mechanical energy during the first year of operation can be calculated by multiplying the amount of energy consumed by the electricity energy price, p_E, resulting in:

$$C_{EM}(P(t)) = E_M(P(t)) \cdot p_E = p_E \cdot \int_0^T P(t) dt = T \cdot P_m \cdot p_E$$

Finally, the cost of the energy loss during the first year of operation can be calculated using the power-loss model (3), written as:

$$C_{EL}(P_R,P(t)) = E_L(P_R,P(t))\cdot p_E \approx T\cdot\left(k_{LFF} + k_{LFV}\cdot P_R + (k_{LVF} + k_{LVV}\cdot P_R)\cdot\frac{P_{RMS}^2}{P_R^2} \right)\cdot p_E$$

As a result, the total cost of the first year of operation of the motor can be expressed as the sum of the annual cost of the mechanical energy and the annual cost of the losses during the first year:

$$\begin{aligned} C_O(P_R,P(t)) &= C_M(P(t)) + C_{EL}(P_R,P(t)) \\ &\approx T\cdot\left(P_m + k_{LFF} + k_{LFV}\cdot P_R + (k_{LVF} + k_{LVV}\cdot P_R)\cdot\frac{P_{RMS}^2}{P_R^2} \right)\cdot p_E \end{aligned}$$

In order to calculate the cumulated present or actual value of the cost of the energy loss throughout the whole in-service life of the motor, C_{PEL}, it is necessary to consider the depreciation effect of the money in each of the N future years of expected life of the motor, by means of the discount rate, d, and the effect of the annual increase in the price of energy, Δp_E, resulting in:

$$\begin{aligned} C_{PEL} = NPV(C_{EL}(P_R,P(t))) &= \sum_{n=1}^{N} C_{EL}(P_R,P(t))\frac{(1+\Delta p_E)^n}{(1+d)^n} = \sum_{n=1}^{N} C_{EL}(P_R,P(t))\frac{1}{(1+d_{eq})^n} \\ &= C_{EL}(P_R,P(t))\frac{(1+d_{eq})^N - 1}{d_{eq}(1+d_{eq})^N} = C_{EL}(P_R,P(t))\cdot k_P \end{aligned}$$

where the equivalent discount rate is:

$$d_{eq} = \frac{d - \Delta p_E}{1+\Delta p_E}$$

and the cumulative present value coefficient is:

$$k_P = \frac{(1+d_{eq})^N - 1}{d_{eq}(1+d_{eq})^N}$$

The present or actual cost of the motor over its N expected years of in-service life, considering an equivalent discount rate, d_{eq}, can be expressed as:

$$\begin{aligned} LCC(P_R,P(t)) &= -I(P_R) - \sum_{n=1}^{N}\left(C_M(P(t)) + C_{EL}(P_R,P(t))\right)\frac{(1+\Delta p_E)^n}{(1+d)^n} - C_D(P_R) + V_R(P_R) \\ &= -I(P_R) - \left(E_M(P(t)) + E_L(P_R,P(t))\right)\cdot p_E\cdot k_P - C_D(P_R) + V_R(P_R) \\ &\approx -k_{EQ}\cdot(c_{PF} + c_{PV}\cdot P_R) - T\cdot\left(P_m + k_{LFF} + k_{LFV}\cdot P_R + (k_{LVF} + k_{LVV}\cdot P_R)\cdot\frac{P_{RMS}^2}{P_R^2} \right)\cdot p_E\cdot k_P \end{aligned}$$

Therefore, the optimum rated power of the motor, which minimizes the LCC, can be obtained by cancelling out the partial derivative of the LCC, with respect to the rated power, resulting in:

$$\frac{\partial LCC(P_R,P(t))}{\partial P_R} = -k_{EQ}\cdot c_{PV} - \left(k_{LFV} - \left(\frac{2k_{LVF}\cdot P_R}{P_R^4} + \frac{k_{LVV}}{P_R^2} \right)\cdot P_{RMS}^2 \right)\cdot T\cdot p_E\cdot k_P = 0$$

This minimum condition can also be written as:

$$k_{EQ} \cdot c_{PV} \cdot P_R^3 + \left(k_{LFV} \cdot P_R^3 - \left(2k_{LVF} + k_{LVV} \cdot P_R \right) \cdot P_{RMS}^2 \right) \cdot T \cdot p_E \cdot k_P = 0$$

Grouping the coefficients of the cubic equation:

$$\left(k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P \right) \cdot P_R^3 - k_{LVV} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P \cdot P_R - 2k_{LVF} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P = 0$$

Accordingly, the minimum condition can be written as:

$$P_R^3 - \frac{k_{LVV} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P} P_R - \frac{2k_{LVF} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P} = 0 \, ,$$

which can be solved using Cardano's method. Therefore, the optimum rated power, which minimizes the LCC of the motor, results in:

$$P_{R\,LCCmin} = \sqrt[3]{\frac{k_{LVF} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P} + \sqrt{\Delta}} + \sqrt[3]{\frac{k_{LVF} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P} - \sqrt{\Delta}}$$

where the discriminant, Δ, is:

$$\Delta = \left(\frac{k_{LVF} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P} \right)^2 - \left(\frac{k_{LVV} \cdot P_{RMS}^2 \cdot T \cdot p_E \cdot k_P}{3(k_{EQ} \cdot c_{PV} + k_{LFV} \cdot T \cdot p_E \cdot k_P)} \right)^3$$

It is worth noting that, when the equivalent discount rate approaches zero, the present operating cost, that is, the present cost of the energy throughout the life-cycle, approaches N times the annual cost of the energy:

$$\begin{aligned} \lim_{d_{eq} \to 0} \left(C_{PO}(P_R, P(t)) \right) &= \lim_{d_{eq} \to 0} \left(\sum_{n=1}^{N} \left(C_M(P(t)) + C_{EL}(P_R, P(t)) \right) \frac{1}{(1+d_{eq})^n} \right) \\ &= \left(C_M(P(t)) + C_{EL}(P_R, P(t)) \right) \cdot N = \left(E_M(P(t)) + E_L(P_R, P(t)) \right) \cdot p_E \cdot N \\ &= E(P_R, P(t)) \cdot p_E \cdot N \end{aligned}$$

This means that, if the decommissioning cost is approximately cancelled out by the residual value, and the initial investment can be disregarded when compared with the present operating costs, which is often the case, then both optimum conditions, minimum LCC and minimum energy (or energy loss), come into play:

$$\begin{aligned} \lim_{d_{eq} \to 0} \left(LCC(P_R, P(t)) \right) &= \lim_{d_{eq} \to 0} \left(-I(P_R) - C_{PO}(P_R, P(t)) - C_D(P_R) + V_R(P_R) \right) \\ &\approx \lim_{d_{eq} \to 0} \left(C_{PO}(P_R, P(t)) \right) = \lim_{d_{eq} \to 0} \left(\sum_{n=1}^{N} \left(C_M(P(t)) + C_{EL}(P_R, P(t)) \right) \frac{1}{(1+d_{eq})^n} \right) \\ &= \left(C_M(P(t)) + C_{EL}(P_R, P(t)) \right) \cdot N = \left(E_M(P(t)) + E_L(P_R, P(t)) \right) \cdot p_E \cdot N \\ &= E(P_R, P(t)) \cdot p_E \cdot N \end{aligned}$$

Consequently, the optimum rated power for minimum LCC approaches the optimum rated power for minimum energy or losses:

$$P_{R\,LCC\min} \approx \lim_{d_{eq} \to 0} \left(P_R(LCC_{\min}) \right) \approx P_R(E_{L\min}) = P_{R\,EL\min}$$

In other words, the optimum rated power minimizing the energy or energy loss is a practical upper limit for the optimum rated power minimizing the LCC,

$P_{R\,LCCmin} \leq P_{R\,PLmin}$. This result can be useful in those common cases where the list price of the motors is no longer available, as will be shown later.

4. Case Study

In the EU, on 1 January, 2017, the third and last tier of the Energy Using Products (EUP) Directive for electric motors (EU Ecodesign Directive) [6,7] came into force. Since then, the Minimum Energy Performance Standards (MEPS) for electric motors require new motors sold in the EU market (with a rated output from 0.75 kW-355 kW) must satisfy the IE3 efficiency class (or IE2, if fitted to a Variable Speed Drive-VSD). For that reason, the proposed method will be tested with IE3 (premium efficiency) motors, despite the low level of losses for this efficiency class. For the purpose of comparison, results for IE2 (high efficiency) motors will also be shown.

The reference scenario of the case study addresses the project-stage selection of the techno-economic optimum rated power (duty type S1), P_R, of an IE3, line-operated single-speed cage induction motor from Table 1 to drive a time-variable mechanical power load, $P(t)$, for $T = 8760$ operating hours a year. Figure 4 shows the considered annual time-variable mechanical power load, $P(t)$, in which $P_{100\%} = 30$ kW has been selected as the 100% power load.

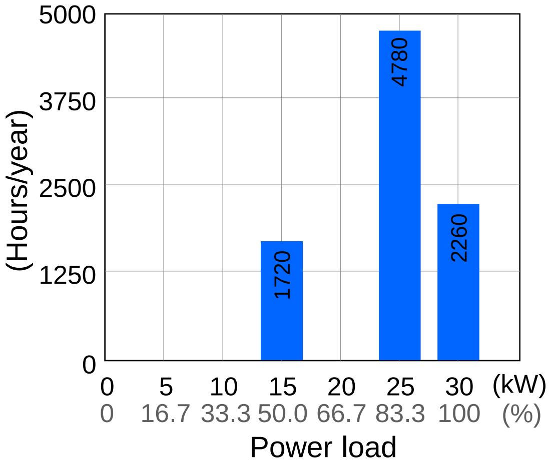

Figure 4. Annual time-variable mechanical power load, $P(t)$.

Accordingly, the annual mean and the RMS values of the mechanical power load result in:

$$P_m = \frac{1}{T}\sum_k P(t_k)\cdot t_k = 24.3\,\mathrm{kW}$$

$$P_{RMS} = \sqrt{\frac{1}{T}\sum_k P^2(t_k)\cdot t_k} = 27.7\,\mathrm{kW}$$

As a result, following the conventional method, a motor rated P_R(RMS) = 30 kW should be chosen, which is the first rated power over the value P_{RMS} = 27.7 kW, as found in the manufacturer's catalogue (Table 1). It is easy to check that the value of the peak or maximum load power, $P_{MAX} = P_{100\%} = 30$ kW, does not exceed the rated power of the motor at any time, since P_R(RMS) = 30 kW ≥ P_{MAX} = 30 kW.

Table 3 summarizes the coefficients of the power-loss model and the purchase-cost model of the IE3 and IE2 motors, whose rated powers are 30 kW, 37 kW and 45 kW, as determined by linear regression fitting (see Appendix B for a simplified calculation of these coefficients). As will be shown, this two-step range of power rating considers the expected optimum rated power of the motor. A discount factor, $k_d = 0.4$, and a residual value equivalent to the sum of the decommissioning and the auxiliary costs ($k_R = k_D + k_A$) have been considered for the sake of simplicity.

Table 3. Coefficients of the power-loss model and the purchase-cost (list price) model for motors rated at 30 kW, 37 kW and 45 kW.

Rated Power	Power losses $P_L(P_R,P_{pu}) = k_{LF}(P_R) + k_{LV}(P_R)\cdot P^2_{pu}$		List price
P_R (kW)	k_{LF} (kW)	k_{LV} (kW)	C_P (€)
IE3 (premium efficiency)			
30	0.7355	1.3197	3338
37	0.8398	1.5707	4068
45	0.9955	1.7779	4882
Linear regression	$k_{LF}(P_R) \approx k_{LFF} + k_{LFV}\cdot P_R$ $k_{LFF} = 0.2080$ $k_{LFV} = 0.0174$	$k_{LV}(P_R) \approx k_{LVF} + k_{LVV}\cdot P_R$ $k_{LVF} = 0.4197$ $k_{LVV} = 0.0304$	$C_P(P_R) \approx c_{PF} + c_{PV}\cdot P_R$ $c_{PF} = 254.20$ $c_{PV} = 102.91$
IE2 (high efficiency)			
30	0.9247	1.5909	3025
37	1.1401	1.7896	3651
45	1.4145	1.9359	4444
Linear regression	$k_{LF}(P_R) \approx k_{LFF} + k_{LFV}\cdot P_R$ $k_{LFF} = -0.0607$ $k_{LFV} = 0.0327$	$k_{LV}(P_R) \approx k_{LVF} + k_{LVV}\cdot P_R$ $k_{LVF} = 0.9176$ $k_{LVV} = 0.0229$	$C_P(P_R) \approx c_{PF} + c_{PV}\cdot P_R$ $c_{PF} = 170.93$ $c_{PV} = 94.71$

Figure 5 shows the evolution of the EU-28 average semi-annual electricity prices for industrial consumers (Band-IC: annual consumption between 0.5 and 2 GWh), all taxes and levies included [60]. Accordingly, an electricity price of p_E = 148.55 €/MWh, the EU-28 average electricity price in 2015, has been considered in the reference scenario. The linear regression of price data fitting shows that the electricity price grows at an average annual rate of 2·2.1625 = 4.325 €/MWh, or $\Delta p_E = (4.325/148.55)\cdot 100$ = 2.91%/year.

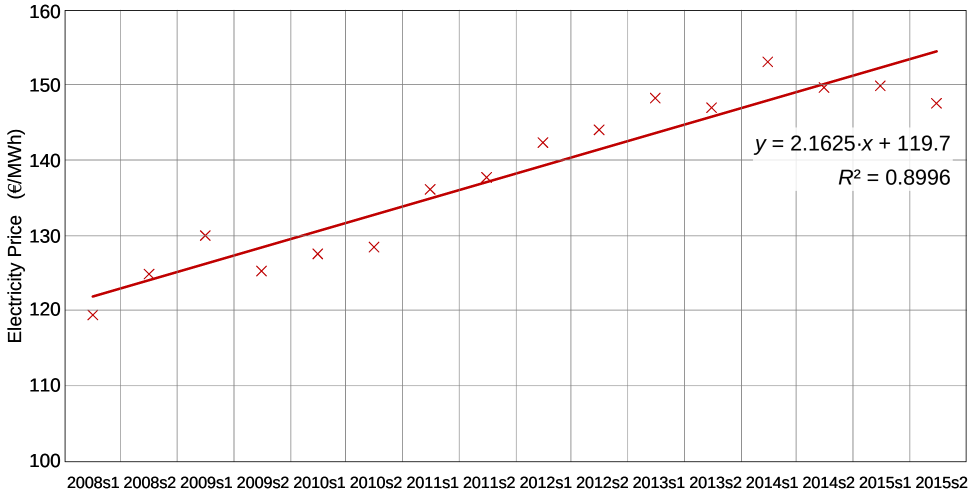

Figure 5. 2008-2015: EU-28 average semi-annual electricity prices for industrial consumers (Band-IC: annual consumption between 0.5 and 2 GWh), all taxes and levies included (Eurostat code [nrg_pc_205]). Data fitting by linear regression.

Table 4 shows the average lifetime of an AC motor in terms of rated power [50]. Accordingly, a lifespan of N = 15 years has been used to calculate the LCC of the motor.

Table 4. Average lifetime of an AC motor in terms of rated power [50].

0.75 kW – 1.1 kW	1.1 kW – 11 kW	11 kW – 110 kW	110 kW – 370 kW
10 years	12 years	15 years	20 years

Finally, a (unfavourable) discount rate, d = 5%, has been used in the reference scenario. This value is slightly higher than the average real yield on longer-term government debt in the EU over the period 2001-2016, 4.61%, as shown in Table 5 [61]; and higher than the "social discount rate" of 4% recommended in Tool #54 of the Toolbox Complement [62] to the *Better Regulation Guideline* of the EU.

Table 5. 2001-2016: EU-28 average annual real yield on longer-term government debt [Eurostat code: teimf050].

Year	2001	2002	2003	2004	2005	2006	2007	2008
EU-28 bond yields (%)	5.30	5.06	5.00	4.91	4.81	4.72	4.60	4.49
Year	2009	2010	2011	2012	2013	2014	2015	2016
EU-28 bond yields (%)	4.41	4.37	4.35	4.34	4.34	4.35	4.36	4.38

4.1 Results and discussion

Table 6 and Figure 6 summarize the main results of the reference scenario of the case study considered. Since the value of the RMS power of the load profile was P_{RMS} = 27.7 kW, a motor rated P_R(RMS) = 30 kW should be selected, according to the conventional rule. If an IE3 motor were selected, this motor would drive the mechanical load with an annual energy loss of 16.35 MWh/y, and a whole LCC of 438.99 k€.

According to the proposed method, the optimum rating of the motor with minimum annual energy loss is $P_{R\ ELmin}$ = 46.31 kW > P_{RMS} = 27.7 kW. As a result, a motor with an optimum rated power, $P_R(E_{Lmin}) = 45$ kW, should be selected from the manufacturer’s catalogue (since the energy loss corresponding to the motor rated 37 kW is higher).

It is worth noting that this result could also be well anticipated with the regression line of minimum losses in Figure 2:

- Since the value of the RMS power of the load, $P_{RMS} = 27.7$ kW, is placed between the crossing points $P_{37\text{-}45}$ and $P_{45\text{-}55}$, (24.08 kW < $P_{RMS} = 27.7$ kW ≤ 32.87 kW), the minimum energy loss corresponds to the motor rated 45 kW.
- The approximate value of the minimum annual energy loss can now be estimated with (4):

  $$E_L(P_{R\,PLmin}, P = P_{RMS}) = 8760 \cdot P_L(P_{R\,PLmin}, P_{RMS})$$
  $$= 8760 \cdot (0.32 + 0.049 \cdot 27.7) = 14.69 \text{ MWh/y}$$

  which is very close to the exact result (14.62 MWh/y).

Table 6. Summary of results for the reference scenario of the case study.

<table>
<tr><th colspan="6">IE3 (premium efficiency)</th></tr>
<tr><th>Rated power P_R (kW)</th><th>Energy loss E_L (MWh/y)</th><th>Energy E (MWh/y)</th><th>Energy efficiency η_E (%)</th><th>Life cycle cost $\lvert LCC \rvert$ (k€)</th><th>Present cost of energy losses $C_{PEl}/\lvert LCC \rvert$ (%)</th></tr>
<tr><td>P_{RMS} = *27.70*</td><td>*17.10*</td><td>*230.20*</td><td>*91.97*</td><td>*440.28*</td><td>*7.40*</td></tr>
<tr><td>30</td><td>16.35</td><td>229.45</td><td>92.33</td><td>438.99</td><td>7.09</td></tr>
<tr><td>37</td><td>15.05</td><td>228.15</td><td>92.94</td><td>436.95</td><td>6.56</td></tr>
<tr><td>$P_{R\,LCCmin}$ = *42.65*</td><td>-</td><td>-</td><td>-</td><td>*436.58*</td><td>-</td></tr>
<tr><td>**45**</td><td>**14.62**</td><td>**227.72**</td><td>**93.14**</td><td>**436.63**</td><td>**6.37**</td></tr>
<tr><td>$P_{R\,ELmin}$ = *46.31*</td><td>*14.61*</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>55</td><td>14.85</td><td>227.95</td><td>93.03</td><td>437.71</td><td>6.46</td></tr>
<tr><td>75</td><td>16.47</td><td>229.57</td><td>92.27</td><td>442.05</td><td>7.10</td></tr>
<tr><th colspan="6">IE2 (high efficiency)</th></tr>
<tr><th>Rated power P_R (kW)</th><th>Energy loss E_L (MWh/y)</th><th>Energy E (MWh/y)</th><th>Energy efficiency η_E (%)</th><th>Life cycle cost $\lvert LCC \rvert$ (k€)</th><th>Present cost of energy losses $C_{PEl}/\lvert LCC \rvert$ (%)</th></tr>
<tr><td>P_{RMS} = *27.70*</td><td>*21.00*</td><td>*234.10*</td><td>90.15</td><td>*447.51*</td><td>*8.93*</td></tr>
<tr><td>30</td><td>20.05</td><td>233.14</td><td>90.59</td><td>445.83</td><td>8.56</td></tr>
<tr><td>**37**</td><td>**18.73**</td><td>**231.83**</td><td>**91.21**</td><td>**443.73**</td><td>**8.04**</td></tr>
<tr><td>$P_{R\,LCCmin}$ = *38.65*</td><td>-</td><td>-</td><td>-</td><td>*443.67*</td><td>-</td></tr>
<tr><td>$P_{R\,ELmin}$ = *40.14*</td><td>*18.63*</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>45</td><td>18.82</td><td>231.92</td><td>91.17</td><td>444.37</td><td>8.07</td></tr>
<tr><td>55</td><td>20.06</td><td>233.16</td><td>90.59</td><td>447.29</td><td>8.54</td></tr>
<tr><td>75</td><td>24.10</td><td>237.20</td><td>88.69</td><td>456.14</td><td>10.06</td></tr>
</table>

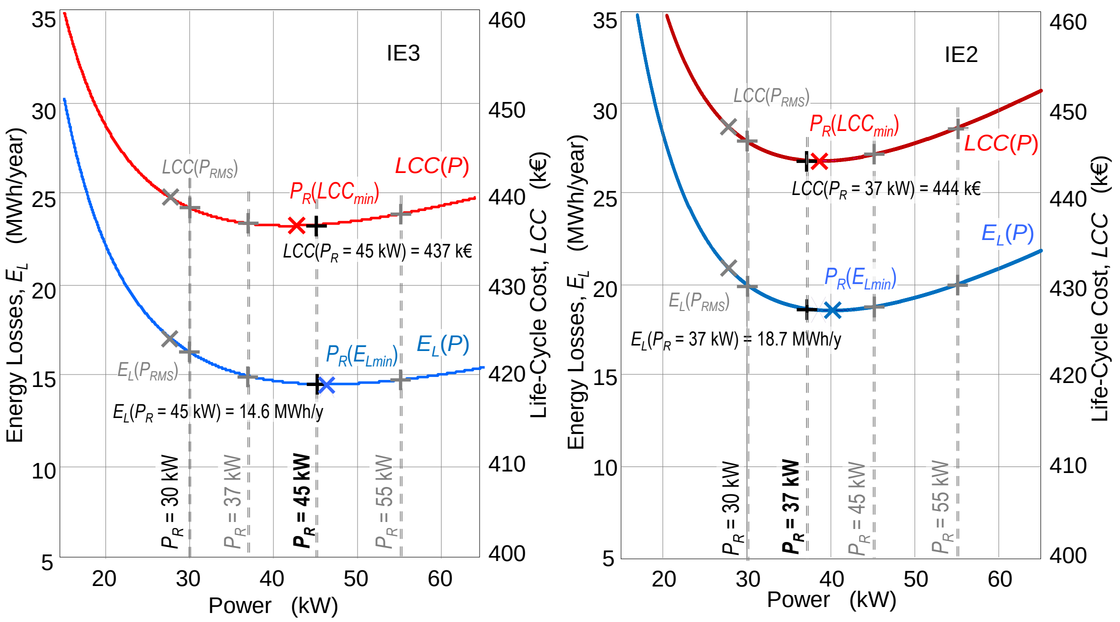

Figure 6. Variation of the annual energy loss, $E_L(P_R)$, and the LCC, $\left|LCC(P_R)\right|$, with the rated power of the motor for IE3 motors (left-hand side) and for IE2 motors (right-hand side).

If the minimum LCC is considered, then the proposed method leads to a motor with an optimum rated power of $P_{R\,LCCmin} = 42.65$ kW ($P_{RMS} = 27.7\text{ kW} < P_{R\,LCCmin} = 42.65\text{ kW} < P_{R\,ELmin} = 46.31$ kW). Accordingly, a motor with a rated power of $P_R(LCC_{min}) = 45$ kW should be selected from the manufacturer's catalogue (the LCC corresponding to the motor rated 37 kW is slightly higher).

As can be observed, for the considered case, the rated powers of the motors with minimum annual energy loss and minimum LCC coincide, i.e., $P_R(E_{Lmin}) = 45\text{ kW} = P_R(LCC_{min}) = 45$ kW, and both result in being two steps higher in the manufacturer's catalogue than the rated power of the motor based on the RMS power, $P_R(RMS) = 30$ kW.

The techno-economic optimum IE3 rated power would:

- Reduce the annual energy loss up to $E_L(P_R(E_{Lmin}) = P_R(LCC_{min}) = 45\text{ kW}) = 14.62$ MWh/y, which constitutes 10.59% (1.73 MWh/y) less than that corresponding to the conventionally rated motor $P_{R\,RMS} = 30$ kW.
- Reduce the whole LCC up to $\left|LCC(P_R(E_{Lmin}) = P_R(LCC_{min}) = 45\text{ kW})\right| = 436.63$ k€, which is 0.54% (2.36 k€) less than that corresponding to the conventionally rated motor $P_{R\,RMS} = 30$ kW.
- Increase the overall energy efficiency up to $\eta_E(P_R(E_{Lmin}) = P_R(LCC_{min}) = 45\text{ kW}) = 93.14\%$, which is 0.81% greater than that corresponding to the conventionally rated motor $P_{R\,RMS} = 30$ kW. Although the amount of the increase in energy efficiency would seem to be small, it is in fact markedly greater than the increase in the rated efficiency between the conventionally rated motor, $P_{R\,RMS} = 30$ kW, and the optimum rated motor, $\eta_R(P_R = 45\text{ kW}) - \eta_R(P_R = 30\text{ kW}) = 94.2 - 93.6 = 0.6\%$.
- Reduce the cumulative present cost of the losses in the LCC up to $C_{PEL}(P_R(E_{Lmin}) = P_R(LCC_{min}) = 45\text{ kW}) = 27.83$ k€ (6.37% of LCC), which is 10.59% (3.30 k€) less than that corresponding to the conventionally motor rated

at $P_{R\,RMS}$ = 30 kW (31.13 k€, 7.09% of the LCC). Accordingly, the increment of the initial cost, $I(P_R = 45\text{ kW}) - I(P_R = 30\text{ kW}) = 926$ € is offset by the cost savings over 5.9 years, that is, only slightly more than a third of the expected life of the motor.

A rough extrapolation of the particular results of this IE3 case to the 2015 data of electric motor consumption in the EU-28 sectors of industry and services would lead to:

- an annual potential energy saving of 7.48 TWh/y (0.75% total saving),
- an annual potential saving in operating costs of 14.24 G€/y, and
- an annual potential saving in emissions of CO_2eq of 2.80 million t(CO_2eq)/y.

Figure 6 (left-hand side) shows the evolution of the annual energy loss, $E_L(P_R)$, and the whole LCC, $LCC(P_R)$, with the rated power of the motor. This figure (and Table 6) clearly confirm that the optimum rated power, based on the minimum LLC, $P_{R\,LCCmin}$ = 42.65 kW, is a little lower than the optimum based only on energy or energy loss, $P_{R\,ELmin}$ = 46.31 kW, due to the effect of considering of the initial cost of the motor. This figure also shows that the RMS power of the load, P_{RMS} = 27.7 kW, the rated power based on the minimum LLC, $P_{R\,LCCmin}$ = 42.65 kW, and the optimum rated power based only on energy or energy loss, $P_{R\,ELmin}$ = 46.31 kW, are both in an increasing sequence.

Figure 6 (left) shows that both the energy loss and the LCC are L-shaped. For IE3 motors, as the power grows, both curves fall to the minimum points, after which they increase very slowly. As a result, both curves exhibit rather flat minimum points. Table 6 shows that the performance indicators of the motor rated 55 kW are only a little worse than those corresponding to the optimum rated 45 kW motor (1.6% for energy and 0.2% for the LCC), although it is still better than the conventional motor rated $P_{R\,RMS}$ = 30 kW (1.50 MWh/y less energy and 1.28 k€ less LCC). This rather flat minimum region could be advantageous in the design of a motor-purchasing policy with a reduced number of rated powers, since there is a broad range of mechanical loads surrounding the flat region of the minimum point.

For the techno-economic optimum rated motor, the RMS load represents a normalized or relative load of $P_{pu} = P_{RMS}/P_{R\ LCCmin} = 27.7/45 = 0.6156$, which means that the temperature of the windings will remain well below the allowable maximum. Considering class F insulation (155ºC) with a temperature rise B ($\Delta\theta_M$ = 130 – 50 = 80 K, a standard air-cooling temperature of 40°C and 10 K for the hotspot temperature margin), which is the most common requirement across industry today, and also considering that the temperature rise is proportional to the power losses, the temperature rise results in:

$$\frac{\Delta\theta}{\Delta\theta_M} = \frac{\Delta\theta(P_R = 45\text{ kW}, P_{RMS} = 27.7\text{ kW})}{\Delta\theta(P_R = 45\text{ kW}, P = 45\text{ kW})} = \frac{P_L(P_R = 45\text{ kW}, P_{RMS} = 27.7\text{ kW})}{P_L(P_R = 45\text{ kW}, P_R = 45\text{ kW})}$$

$$= \frac{0.9955 + 1.7779 \cdot 0.6156^2}{0.9955 + 1.7779 \cdot 1^2} = 0.60$$

Therefore, the reduction in the temperature rise under its allowable maximum is:

$$\Delta\theta_M - \Delta\theta = (1 - 0.6018) \cdot \Delta\theta_M = (1 - 0.6018) \cdot 80 = 31.85\text{ K}$$

An approximation of the Montsinger’s rule states that a temperature rise of 10 K halves the expected lifetime of the isolations. Conversely, a reduction in the temperature of 10

K doubles the expected thermal life of the insulations. Accordingly, it is expected that the thermal life of the optimum rated motor will extend well beyond the 15 years initially expected.

The bottom part of Table 6 (Figure 6) shows that similar results are reached with IE2 motors, but with an optimum rated power of 37 kW. Even though the energy loss (+4.11 MWh/y) and the LCC (+7.10 k€) of this IE2 motor are higher than those corresponding to the 45 kW IE3 motor, they still remain lower than those corresponding to the IE2 motor rated $P_{R\,RMS}$ = 30 kW (–2.27 MWh/y and –3.78 k€, respectively). The increment of the initial cost for the optimum IE2 rated motor, $I(P_R$ = 37 kW) - $I(P_R$ = 30 kW) = 376 €, is offset by the savings in costs over 2.7 years, that is, less than a fifth of the expected life of the motor.

Table 6 also shows that the performance indicators of the IE2 motor rated at 45 kW are only a little worse than those corresponding to the optimum rated motor at 37 kW, but are still better than the conventional motor rated at $P_{R\,RMS}$ = 30 kW.

It is worth noting that the difference (saving) in the LCC of the IE3 and IE2 optimum rated power motors (7.10 k€), is almost 10 times the difference in initial cost (739 €).

A rough extrapolation of the particular results of the IE2 case to the 2015 data of electric motor consumption in the EU-28 sectors of industry and services would lead to:

- an annual potential energy saving of 5.59 TWh/y (0.56% total saving),
- an annual potential saving in operating costs of 9.90 G€/y, and
- an annual potential saving in emissions of CO_2eq of 2.09 million t(CO_2eq)/y.

As expected, Figure 6 shows that the curves of the energy loss and the LCC of IE2 motors are higher than the corresponding curves for IE3 motors. This figure also shows that, while curves of IE3 motors are L-shaped, the higher losses of IE2 motors, as well as the greater difference in losses between motors consecutively rated, resulted in the curves of IE2 motors being more V-shaped. For IE2 motors, as the power grows, the curve falls to the minimum point faster than does the curve for the IE3 motors. As the minimum IE2 curves also grow faster than those for IE3 motors, IE2 curves exhibit a more marked minimum point and the optimum rated motor is closer to the RMS power. Conversely, the higher the efficiency class, the greater the distance between the optimum rating and the RMS power.

The higher value of the rated power of the optimized motors may imply a certain degree of conflict between the size of the motor frame and the room available, which could lead to extra costs in commissioning and installation. In the project stage, the difficulties caused by size are easily manageable, but can prove to be a limitation when replacing an old motor. Nevertheless, a survey of the IE3 motor catalogue shows that, of the 18 motors recorded, there are only three motors (rated powers) that do not share the shaft height with any other motor. The remaining 15 motors (rated power) share a shaft height with at least one motor. For the case of the 25 motors in the IE2 catalogue, there are only four motors (rated powers) that do not share a shaft height, while the remaining 21 motors (rated power) share a shaft height with at least one motor.

Another conflicting situation may occur when considering the replacement of a motor driving an application with a growing torque-speed load curve. In such a case, it should be borne in mind that, the higher the motor efficiency class and rated power, the higher the shaft torque, the speed (lower slip), and the mechanical power delivered. Accordingly, it may happen that the reduction in power losses of the new motor (greater rated power or better efficiency class) was less than the increase in the mechanical power in the shaft, which would lead to an increase in active power consumption [63,64]. For the sake of simplicity, the small change in the operating point (torque and speed or slip) has not been taken into account in this work. Nevertheless, in the design or project stage of a new application, the engineer can easily adjust the application to the chosen motor (greater rated power or better efficiency class); thus, the slight speed increase in the selected motor ought not to pose an issue [19].

As previously mentioned, the greater value of the optimized rated power leads the motor to operate with a reduced relative load, which means an extension to the expected motor lifetime, since a longer winding insulation and bearing lifetime are both expected. As a result of the lower operating temperature, an increase in the motor endurance to overloads or voltage unbalance can also be expected, as well as a better tolerance towards the effects of the harmonic distortion [19]. These all represent significant advantages of optimized rated power motors, since, as mentioned, reliability is the main focus of plant engineers.

4.2 Sensitivity test

In order to test the robustness of the solution suggested by the proposed method, an analysis of the influence of the main parameters on the solution for the reference case scenario is performed. Starting with the reference scenario, this test analyses the effect on the optimum rating of varying, across a broad range, *ceteris paribus*, the operational hours per year, T, the price of the energy, p_E, the discount factor in the purchase cost, k_d, the discount rate, d, and the lifespan, N. Figure 7 summarizes the results for IE3 motors.

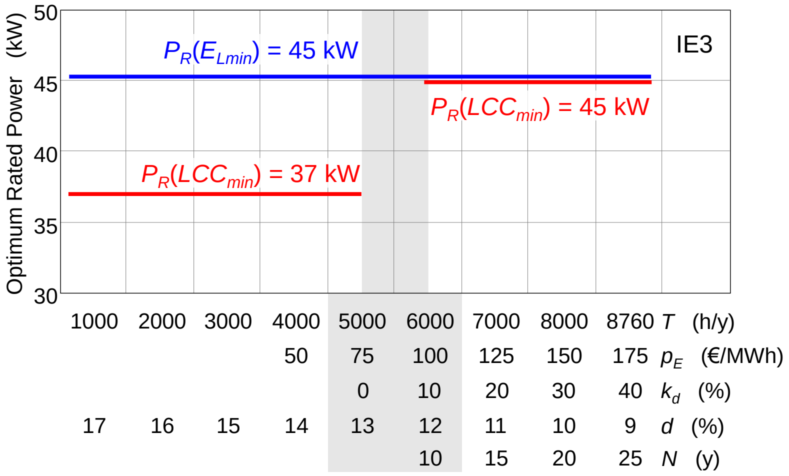

Figure 7. IE3 motors. Optimum rated power for minimum energy loss, $P_R(E_{Lmin})$, and minimum LCC, $P_R(LCC_{min})$: Influence of the operating hours per year, T, the cost of energy, p_E, the discount factor in the purchase cost, k_d, the discount rate, d, and the life span, N.

It can be observed that the proposed solution is highly robust since the optimum rated power for the minimum LCC only shifts from its value in the reference scenario, $P_R(LCC_{min})$ = 45 kW, to $P_R(LCC_{min})$ = 37 kW, when:

- the operating hours per year are reduced to 5000 hours/year or fewer (first row below the graph),
- the price of energy falls to 75 €/MWh or less,

- the discount in the purchase cost is null,
- the discount rate increases up to 13% or more, and
- the lifespan of the motor is reduced to less than 10 years.

The optimum rating for minimum energy loss, $P_R(E_{Lmin})$ = 45 kW, remains invariant for any change in the operational hours per year (not influenced by the remaining magnitudes).

The results for the IE2 motor are even more robust as they stay within the reference case solutions for all the variations considered. In this case, the optimum rated power for the minimum LCC reached the value of the minimum energy loss, $P_R(LCC_{min}) = P_R(E_{Lmin})$ = 37 kW, which prevents any capacity for improvement.

4.3 Other tests

The proposed optimal power rating method has also been tested for lower and higher mechanical loads and for two additional worldwide manufacturers of motors. Table 7 summarizes the results for the energy loss and the LCC corresponding to five new cases with IE3 and IE2 motors [52,55]. The same percentage time-power profile in Figure 5 is considered for all these cases, but the 100% power load, $P_{100\%}$, has been adapted for every case. The first two columns of Table 7 indicate the 100% power load, $P_{100\%}$, which is considered for every case, and the corresponding value of the RMS power of the mechanical load, P_{RMS}. The remaining columns summarize the results corresponding to the conventional RMS rated motor and the optimized results for minimum losses and minimum LCC corresponding to IE3 and IE2 motors.

Table 7. Summary of results for the percentage time-power profile of Figure 5 and different values of the 100% power load, $P_{100\%}$.

Load		**RMS**					**IE2**			**IE3**		
100% power $P_{100\%}$ (kW)	**RMS power P_{RMS} (kW)**	**RMS rated power $P_R(RMS)$ (kW)**	**Energy loss E_L (MWh/y)**		**Life-cycle cost $\lvert LCC \rvert$ (k€)**		**Optimum rated power $P_{R\,OTP}^*$ (kW)**	**Energy loss E_L (MWh/y)**	**Life-cycle cost $\lvert LCC \rvert$ (k€)**	**Optimum rated power $P_{R\,OPT}^*$ (kW)**	**Energy loss E_L (MWh/y)**	**Life-cycle cost $\lvert LCC \rvert$ (k€)**
			IE2	**IE3**	**IE2**	**IE3**						
11	10.25	**11**	10.09	8.34	170.18	166.82	**$P_{R\,OPT}$ = 18.5**	8.91	168.32	**$P_{R\,OPT}$ = 22**	6.57	164.25
27	24.93	**30**	17.73	14.43	399.97	394.72	**$P_{R\,OPT}$ = 37**	17.11	400.00	**$P_R(E_{Lmin})$ = 45** **$P_R(LCC_{min})$ = 37**	13.49 13.61	393.88 393.59
30	27.70	**30**	19.99	14.43	445.69	394.72	**$P_{R\,OPT}$ = 37**	18.78	443.77	**$P_{R\,OPT}$ = 45**	14.62	436.60
33	30.47	**37**	20.62	16.74	487.86	480.63	**$P_{R\,OPT}$ = 45**	20.17	487.47	**$P_{R\,OPT}$ = 45**	15.86	479.54
66	60.95	**75**	38.03	27.06	968.67	948.72	**$P_{R\,OPT}$ = 90**	30.80	956.18	**$P_R(E_{Lmin})$ = 90** **$P_R(LCC_{min})$ = 75**	26.67 27.07	948.75 948.72
150	138.52	**160**	60.14	51.27	2152.19	2136.01	**$P_{R\,OPT}$ = 160**	60.14	2152.19	**$P_{R\,OPT}$ = 200**	44.90	2126.39

$^*P_{R\,OPT} = P_R(E_{Lmin}) = P_R(LCC_{min})$

It can be observed that, in the majority of instances (10 out of 12 occasions, 83.3%), the rated power of the optimized motor, with minimum losses and minimum LCC, are the same ($P_R(E_{Lmin}) = P_R(LCC_{min})$). This coincidence occurs for all IE2 cases. When the minimum loss criterion is used, the optimum rated power is one step higher than the minimum RMS rated power on seven out of 12 occasions (58.3%), and two steps higher on three occasions (25%). When the minimum LCC criterion is used, the optimum rated power is one step higher than the conventional RMS rated power on six occasions (50.0%), and two steps higher on three occasions (25%).

Table 8 summarizes the results for energy loss corresponding to the same five new cases in Table 7, with motors from two different international manufacturers (Appendix C). The same time-power profile of Figure 5 has been considered for all of these cases. Here, only the minimum loss criterion has been used (and not that of the minimum LCC) because the price lists were not available.

Table 8. Summary of results for the percentage time-power profile of Figure 5 and different values of the 100% power load, $P_{100\%}$. Data from the catalogues of two worldwide manufacturers of motors.

Load		**RMS**			**Optimized IE2**		**Optimized IE3**	
100% power $P_{100\%}$ (kW)	**RMS power P_{RMS} (kW)**	**Rated power $P_R(RMS)$ (kW)**	**Energy loss E_L (MWh/y)**		**Optimum rated power $P_R(E_{Lmin})$ (kW)**	**Energy loss E_L (MWh/y)**	**Optimum rated power $P_R(E_{Lmin})$ (kW)**	**Energy loss E_L (MWh/y)**
			IE2	**IE3**				
		Manufacturer A						
11	10.25	**11**	9.91	8.46	**18.5**	7.75	**18.5**	6.46
27	24.93	**30**	17.22	11.17	**45**	14.33	**55**	11.71
33	30.47	**37**	19.31	16.07	**45**	17.56	**55**	13.72
66	60.95	**75**	32.84	26.69	**110**	32.66	**132**	23.51
150	138.52	**160**	63.84	50.57	**200**	61.16	**200**	46.79
		Manufacturer B						
11	10.25	**11**	9.75	8.12	**22**	7.91	**15**	7.19
27	24.93	**30**	17.22	14.61	**45**	14.33	**45**	11.17
33	30.47	**37**	20.62	16.64	**45**	20.17	**45**	15.86
66	60.95	**75**	32.84	26.93	**90**	30.22	**90**	25.98
150	138.52	**160**	57.88	50.70	**200**	56.68	**200**	47.25

Table 8 shows that the rated power of the optimized motor for minimum losses is always higher than the conventional RMS rated power ($P_R(E_{Lmin}) > P_R(RMS)$). The optimum rated power is one step higher than the conventional RMS rated power in 60% of the instances, two steps higher in 25% of the instances, and even three steps higher in 15% of the instances.

As can be seen, for industry, the proposed techno-economic optimum rating methodology leads to selecting larger (“oversized”) motors, which will work with lower energy needs, under partial load and lower temperature (well under their maximum allowable limit, thereby lengthening their thermal life). This reduces the risk and the associated cost of unplanned downtime, as well as ordinary maintenance costs. The higher initial investment costs of optimum rated motors are largely compensated by the lower operating cost (electricity bill) throughout their whole lifespan. The adoption of the proposed techno-economic optimum rating methodology can also contribute towards meeting the commitment of compulsory or voluntary energy efficiency improvement plans [65].

From a social point of view, the proposed techno-economic optimum rating power methodology leads to the selection of motors of a more energy-efficient nature, which make a better use of energy and reduces CO_2 emissions, thereby contributing towards the achievement of both CO_2 and efficiency targets in the EU's climate and energy package [66].

5. Conclusions

The currently high and increasing price of energy suggests the convenience of upgrading the selection of the rated power of electric motors from that of the conventional RMS method to new methods of a more sophisticated and informed nature. These methods need to integrate the economic aspect of the selection of the rated power, such as the minimum LCC method.

A new methodology to determine the optimum power rating of a single-speed electric motor in order to drive a time-variable mechanical load has been introduced in this paper. The proposed methodology takes into account not only the technical restrictions, due to the power profile of the mechanical load, but also the energy consumption throughout the whole life of the motor: the net present value of purchasing, installing, operating (energy), maintaining and disposing of the motor over its life cycle. Accordingly, the proposed methods can be considered as an extension or evolution of the conventional RMS method, which integrates the economic aspects of the motor rating process. Based on the list of electric motors offered in the catalogue of a manufacturer, the new methodology enables the analytical determination of the rating of the motor which minimizes energy consumption (energy loss) throughout its in-service life and its total LCC. When the list price is not available, as is often the case, the optimal power rating of the motor based on the minimum loss criterion (whereby only the efficiency data from the technical catalogue are needed) provides a good estimation for optimal rating, based on the minimal LCC, since, very often, these two criteria lead to the same power rating.

It has been shown that the points of intersection of the consecutive power-loss curves, $P_{R\ n\text{-}n+1}$, limit the intervals of load power (RMS) in which each rated power motor displays the minimum losses. As those points are aligned into an almost straight line, they can be well represented by fitting a linear regression line. These points and their regression line can approximate the optimum rated power for minimum energy loss. It has also been shown that the optimum rated power for minimum energy loss provides a practical upper limit for the optimum rated power which minimizes the LCC.

The results are highly robust and show that, for IE3 motors, the optimum rated power, for both minimum energy loss and LCC, always ends up as at least one step higher in the manufacturer's catalogue than the rated power based on the RMS power; in fact, it is often two or three steps above.

A rough extrapolation of the results from the IE3 case to the consumption by electric motors in the EU-28 sectors of industry and services should lead to an estimated potential energy saving of 7.48 TWh, an operating cost saving of 14.24 G€, and a saving in CO_2eq emissions of 2.80 million t(CO_2eq) (5.59 TWh, 9.90 G€ and 2.09 million t(CO_2eq) for the IE2 case) for 2015.

In summary, the proposed techno-economic optimal rating method leads to the selection of larger ("oversized") motors that work with a partial load, at a lower temperature (well under their maximum allowable limit, which lengthens their thermal life), thereby reducing the risk of periods of unplanned downtime and ordinary maintenance costs, and demanding and wasting less energy, averting the production of CO_2 emissions, reducing overall costs, and improving competitiveness.

Acknowledgements

This work was partially supported by Spain’s Ministerio de Economía y Competitividad (Ministry of Economy and Competitiveness), with co-funding from the European Commission (European Regional Development Fund), under Grants ENE2014-54115-R, PCIN-2015-043 and ENE2016-77650-R.

Appendix A. List Price of Motors

Table A.1 shows the list price of IEC general-performance cast-iron, cage induction motors designed for low voltage (440 V, 50 Hz), IP 55, IC 411 and insulation class F (temperature rise class B) [57].

Table A.1. List price, C_P (€), of IEC general-performance cast-iron, cage induction motors (CENELEC-design) designed for low voltage (440 V, 50 Hz), IP 55, IC 411 and insulation class F (temperature rise class B) [57].

Rated power	**Two poles (3000 r/m)**		**Four poles (1500 r/m)**		**Six poles (1000 r/m)**		**Rated power**	**Two poles (3000 r/m)**		**Four poles (1500 r/m)**		**Six poles (1000 r/m)**	
P_R (kW)	**IE2**	**IE3**	**IE2**	**IE3**	**IE2**	**IE3**	**P_R (kW)**	**IE2**	**IE3**	**IE2**	**IE3**	**IE2**	**IE3**
0.25			166		200		**22**	2316	2587	2337	2629	3380	3755
0.37	171		186		222		**30**	2900	3213	3025	3338	4673	5153
0.55	193		205		254		**37**	3797	4214	3651	4068	5633	6154
0.75	232		240		303		**45**	4611	5070	4444	4882	6178	6707
1.1	252		274		371		**55**	5633	6154	5716	5946	7557	8181
1.5	299		323		377		**75**	6991	7576	6764	7331	10127	10939
2.2	378		395		533		**90**	8408	9107	7897	8578	12167	13169
3.0	447		472		665		**110**	10240	11072	9806	10599	14794	16041
4.0	535		560		829		**132**	12375	13396	11827	12810	17665	19082
5.5	697		717		1023		**160**	15360	16702	14302	15474	21916	23617
7.5	867	996	903	1040	1406	1581	**200**	19271	20972	18157	19649	27396	29663
11.0	1296	1458	1323	1490	1915	2170	**250**	24373	26262	22672	24373	33630	36276
15.0	1686	1898	1717	1934	2399	2629	**315**	30607	33064	28718	31174		
18.5	2022	2295	1997	2232	2879	3192	**355**	34575	37220	32497	35142		

Table A.2 summarizes the approximation by linear regression fitting of the list price of motors in Table A.1.

Table A.2. Linear fitting of the price list, C_P (€), of IEC motors in Table A.1.

	IE3 (premium efficiency)	**IE2 (high efficiency)**
Two poles (3000 r/m)	$C_P(P_R) \approx 165.59 + 103.88 \cdot P_R$ ($R^2 = 0.9994$)	$C_P(P_R) \approx 116.84 + 74.803 \cdot P_R$ ($R^2 = 0.9955$)
Four poles (1500 r/m)	$C_P(P_R) \approx 306.74 + 97.079 \cdot P_R$ ($R^2 = 0.9994$)	$C_P(P_R) \approx 209.48 + 90.09 \cdot P_R$ ($R^2 = 0.9995$)
Six poles (1000 r/m)	$C_P(P_R) \approx 493.57 + 143.41 \cdot P_R$ ($R^2 = 0.9994$)	$C_P(P_R) \approx 282.133 + 133.90 \cdot P_R$ ($R^2 = 0.9996$)

Appendix B. Approximate Identification of the Power-loss Model and Purchase (List Price) Model

When only two motors, rated P_{RA} and P_{RB}, are considered as candidates for the optimum rating (for example, motors rated P_{RA} = 37 kW and P_{RB} = 45 kW for the reference case in question), the coefficients of the power-loss model and the purchase-cost model can be easily calculated. Table B.1 summarizes the expressions.

Table B.1. Coefficients of the power-loss model and purchase (list price) model in the case of two motors rated P_{RA} and P_{RB}.

Rated power	**Power losses** $P_L(P_R,P_{pu}) = k_{LF}(P_R) + k_{LV}(P_R)\cdot P^2_{pu}$		**List price**
P_R (kW)	k_{LF} (kW)	k_{LV} (kW)	C_P (€)
P_{RA}	k_{LFA}	k_{LVA}	C_{PA}
P_{RB}	k_{LFB}	k_{LVB}	C_{PB}
Approximation	$k_{LF}(P_R) \approx k_{LFF} + k_{LFV}\cdot P_R$	$k_{LV}(P_R) \approx k_{LVF} + k_{LVV}\cdot P_R$	$C_P(P_R) \approx c_{PF} + c_{PV}\cdot P_R$
Coefficients	$k_{LFF} = \frac{k_{LFA}\cdot P_{RB} - k_{LFB}\cdot P_{RA}}{P_{RB} - P_{RA}}$ $k_{LFV} = \frac{k_{LFB} - k_{LFA}}{P_{RB} - P_{RA}}$	$k_{LVF} = \frac{k_{LVA}\cdot P_{RB} - k_{LVB}\cdot P_{RA}}{P_{RB} - P_{RA}}$ $k_{LVV} = \frac{k_{LVB} - k_{LVA}}{P_{RB} - P_{RA}}$	$c_{PF} = \frac{C_{PA}\cdot P_{RB} - C_{PB}\cdot P_{RA}}{P_{RB} - P_{RA}}$ $c_{PV} = \frac{C_{PB} - C_{PA}}{P_{RB} - P_{RA}}$

Appendix C. Efficiency Data on Motors

Tables C.1 and C.2 summarize the efficiency data on general-performance, cast-iron motors designed for low voltage and four poles from manufacturers A and B, respectively.

Table C.1. Cage induction motors from manufacturer A: efficiency data on general-performance, cast-iron motors designed for low voltage (440 V, 50 Hz), four poles, IP 55, IC 411 and insulation class F (temperature rise class B).

Output kW	**IE3 (premium efficiency)**			**IE2 (high efficiency)**		
	Full load 100%	3/4 load 75%	1/2 load 50%	Full load 100%	3/4 load 75%	1/2 load 50%
0.75	82.5	82.3	80.0	79.6	80.2	78.0
1.1	84.1	84.6	83.5	81.4	81.7	79.9
1.5	85.3	85.9	84.9	82.8	83.5	82.0
2.2	86.7	86.7	85.7	84.3	85.1	84.3
3	87.7	87.7	86.7	85.5	86.7	86.0
4	88.6	88.6	87.6	86.6	87.3	86.5
5.5	89.6	89.6	88.6	87.7	89.0	87.7
7.5	90.4	90.4	89.4	88.7	90.3	88.8
11	91.4	91.4	90.4	89.8	90.9	90.8
15	92.1	92.1	91.1	90.6	91.3	91.0
18.5	92.6	93.2	93.2	91.2	92.0	91.9
22	93.0	93.7	93.7	91.6	92.2	91.9
30	93.6	94.3	94.4	92.3	92.8	92.6
37	93.9	94.5	94.4	92.7	93.5	93.5
45	94.2	94.9	95.1	93.1	93.8	93.7
55	94.6	95.1	95.0	93.5	93.9	93.5
75	95.0	95.3	95.0	94.0	94.2	93.8
90	95.2	95.5	95.3	94.2	94.3	93.6
110	95.4	95.8	95.5	94.5	94.6	94.0
132	95.6	95.9	95.9	94.7	94.9	94.6
160	95.8	96.1	96.1	94.9	95.0	94.5
200	96.0	96.3	96.1	95.1	95.3	94.7

Table C.2. Cage induction motors from manufacturer B: efficiency data of general-performance, cast-iron motors designed for low voltage (440 V, 50 Hz), four poles, IP 55, IC 411 and insulation class F (temperature rise class B).

	IE3 (premium efficiency)			**IE2 (high efficiency)**		
Output kW	Full load 100%	3/4 load 75%	1/2 load 50%	Full load 100%	3/4 load 75%	1/2 load 50%
0.75	82.5	82.0	80.0	89.0	89.0	88.7
1.1	84.5	84.5	83.0	89.5	89.5	89.2
1.5	85.5	86.0	84.0	90.2	90.2	89.0
2.2	87.0	87.0	86.5	91.0	91.0	90.6
3	88.0	88.0	87.0	91.6	91.8	91.5
4	88.8	89.1	88.7	92.3	92.5	92.2
5.5	89.7	89.6	89.0	92.8	93.0	92.6
7.5	90.6	90.8	90.5	93.2	93.2	93.0
9.2	91.0	91.0	90.3	93.6	93.7	93.2
11	91.6	91.8	91.1	94.0	93.9	93.6
15	92.3	92.5	92.2	94.4	94.4	93.8
18.5	92.8	92.8	92.2	94.7	94.7	94.1
22	93.2	93.0	92.3	95.0	95.0	94.3
30	93.7	93.6	92.9	95.2	95.2	94.6
37	94.1	94.0	93.4	95.4	95.4	95.0
45	94.4	94.1	93.7	95.4	95.4	94.8
55	94.7	94.7	94.3	95.6	95.6	94.9
75	95.2	95.1	94.5	95.6	95.6	95.0
90	95.4	95.4	94.9	95.7	95.7	95.2
110	95.6	95.5	94.7	95.7	95.7	95.3
132	95.8	95.7	95.1	95.8	95.8	95.4
150	95.9	95.8	95.4	95.8	95.8	95.4
160	96.0	95.9	95.2	95.8	95.8	95.5
185	96.0	96.1	95.5	95.8	95.8	95.5
200	96.0	96.3	96.0	95.8	95.8	95.5
220	96.2	96.1	95.8	95.8	95.9	95.5
250	96.2	96.2	96.0	95.8	95.9	95.5
260	96.2	96.2	96.0	95.8	95.9	95.5
280	96.2	96.0	95.9	95.5	95.0	94.5
300	96.2	96.0	95.8	95.5	95.0	94.5
315	96.3	96.3	96.1	89.0	89.0	88.7
330	96.2	96.0	95.8	89.5	89.5	89.2
355	96.5	96.5	95.9	90.2	90.2	89.0
400	96.2	96.1	95.7	91.0	91.0	90.6
450	96.2	96.1	95.8	91.6	91.8	91.5
500	96.3	96.3	95.9	92.3	92.5	92.2

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