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A review of high-efficiency motors: Specification, policy, and technology

Shyi-Min Lu *

Energy and Environmental Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu 310, Taiwan, ROC

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ABSTRACT

Although nearly all countries in the world have taken active measures to mitigate the greenhouse effect, which is the primary cause of extreme climate change, the electric motor accounts for 40–50% of the total global electricity consumption, thus becoming the primary appliance requiring high-efficiency standards. In this report, a survey is conducted on high-efficiency motor promotion cases in Taiwan and developed countries. Furthermore, a comparison of the policy, technology, regulatory, and trend aspects is summarized. We conclude that the research and technical development of DC brushless motors is the most popular program in the motor industry, and permanent magnet synchronous motors are essentially the most welcome product in the market. The corresponding R&D items include the optimization of the motor design, electromagnetic enhancement of silicon steel sheets, promotion of the advantages of the permanent magnetic field, modification of the wire-winding technology, and improvements in the electronic control technology. Described at the end of this report, the suggested policies for the development of high-efficiency motors are applicable to Taiwan as well as other countries. The energy saving and carbon reduction issues as well as the approach of the high-energy price era have led to the rapid development and popularization of high-efficiency motors.

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* Corresponding author. Tel.: +886 910 354 790.
E-mail address: shyimin@gmail.com

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1. Introduction

Motors are the most important driving components of industrial and consumer products. Motor system applications bring the convenience of automation to humanity. However, a large amount of energy is being consumed worldwide due to a significant increase in the use of related appliances. Currently, based on the viewpoints of the entire industrial sector, motor-related systems consume more than 60% of the total electricity [1,2]. Therefore, enhancing the motor system energy efficiency has become the focus of several countries, which are hopeful that the overall national final energy conservation can be achieved by promoting high-efficiency motors. Additionally, the promotion of motor efficiency specifications developed by international organizations is a growing trend with a direct impact on the production and design of the motor. Through the boom of the "high-efficiency motor era", most traditional motors will eventually be eliminated [3–5].

In recent years, academia and industry have continuously promoted the importance of developing high-efficiency motors. Experts and scholars are engaged in theoretical studies while industries are committed to producing new products and key components, thus aiming to improve the domestic motor efficiency in response to the global trend of high-efficiency motor standards [6].

The structure and principle for both the motor and the generator are opposite. The generator transforms mechanical energy into electrical energy while the motor transforms electrical energy into kinetic energy. Both are equally based on shaft revolution movement, using the same set of agencies to exchange electrical and mechanical energies. As long as the energy input direction is converted, different applications can be achieved. In the grid, the power transmission elements between the generator and the motor are the cables and transformers. A transformer not only alternates voltage but can also reduce energy loss when transmitting power.

As depicted in Fig. 1, the primary types of motor are a DC carbon brush motor (for juicer), induction motor (for fans), synchronous motors (for timers), stepper motor (for factory automation), and other diverse products. As can be seen in Fig. 2, the related industries and applications are numerous.

As illustrated in Fig. 1, the electric motor can be divided into two primary categories: DC motor and AC motor. Furthermore, AC motors can be differentiated into two subcategories: (1) synchronous motors, including sine wave, stepper, brushless, and reluctance; and (2) asynchronous motors, including poly phase, single phase, and AC brushed.

The motor is an important basic element that converts electrical energy to mechanical energy. Motors are indispensable in all economic activities and daily lives. Furthermore, their applications extend to nearly everything and everywhere. Therefore, their influences on industrial development and technological progress are more significant than their industrial economic values [12]. Most motors are designed to operate at a constant speed and provide a constant output; however, modern technology requires different speeds in several electric motor applications. A variable speed drive is a device that regulates the speed and rotational force, or the output torque of mechanical equipment [13]. Adjustable speed drives are normally used in the industry. Generally, induction motors and, recently, permanent magnet synchronous motors are used in these drives. Variable speed drives are primarily used in applications such as electrical vehicles, pumps, elevators, fans, ventilation, heating, robotics, ship propulsion, and air conditioning [14].

Electric motor technologies have persistently surpassed and conquered bottlenecks in the last century due to significant developments, including wide applications in related products as well as daily changing categories. In 1888, American Nikola Tesla applied Faraday's principle of electromagnetic induction to invent the first induction motor. Then, in the mid-1890s, a three-phase AC power

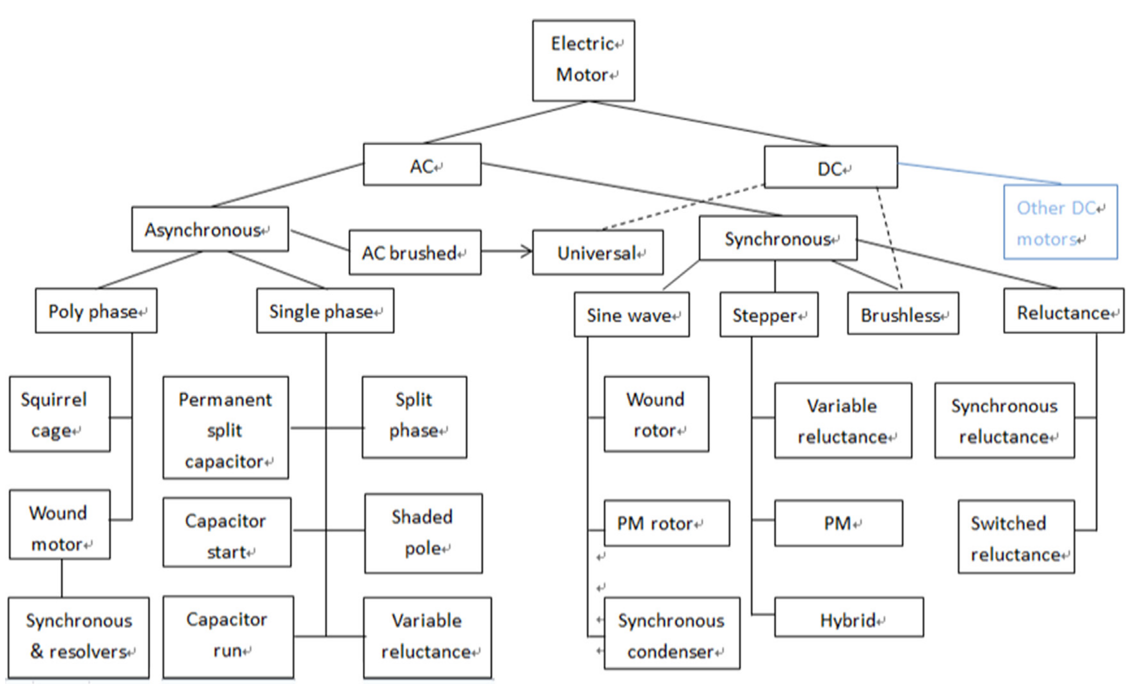

Fig. 1. The application categories for the electric motors [7].

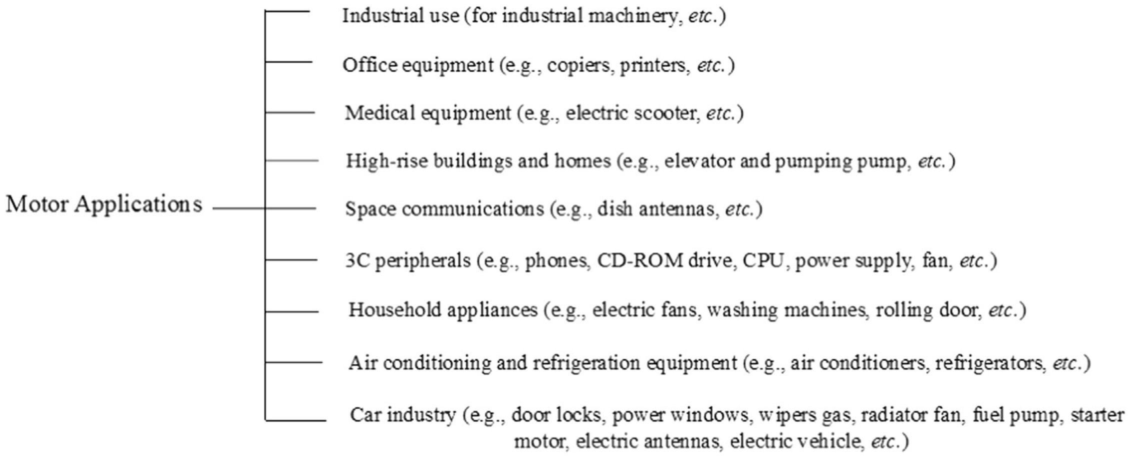

Fig. 2. The wide applications and large related industries of electric motors [8–11].

system was invented. Since then, the motor's commercialization and industrialization has gained considerable popularity. In the initial industrialization and commercialization stages, due to their simple structure, cheap cost and easy maintenance, induction motors were popularly applied to diverse industrial equipment as well as residential and commercial appliances with fixed rotation speeds [15].

The global electric motor sales market is estimated to be approximately USD 91.75 billion in 2015 and expected to grow at a compound annual growth rate of 6.38% from 2015–2020 [16]. The demands for innovative end-user market products, such as electric vehicles, industrial automation equipment and energy-efficient household appliances, and the stepwise rise in the minimum energy efficiency standards in developed countries have led to yearly increases in the demands for higher performance and efficient motors in the global market. This demand is the primary drive behind the future growth of the motor market.

Industrial motors are an important energy consumption index. In accordance with the Kyoto Protocol, developed countries have made a commitment to meet a target of 20% reduction in carbon emissions by 2020, with an extra stipulation of minimum motor efficiency restrictions. Most developed countries have implemented energy efficiency regulations similar to that of the European Union. Several regions have adopted a minimum energy efficiency to restrict the sale and use of industrial motors. For example, the United States has adopted the NEMA (National Electrical Manufacturers Association) standard (equivalent to IE3 premium level) since the end of 2010. Currently, the Super Premium IE4 is being formulated. The EU has clearly stipulated that beginning from 16 June 2011, the efficiency of motors listed for regulation should not be less than IE2. The IE3 is scheduled for implementation in phases during 2015–2017.

Along with the introduction of high-efficiency motors, the purpose of this study is to investigate the effects on Taiwan's industry and thus identify responsive strategies and business opportunities. In this report, a survey of high-efficiency motor promotion cases in Taiwan and developed countries is conducted. Furthermore, a comparison of the policy, technology, regulatory, and trend aspects is summarized.

2. Evolution of high-efficiency motors

In the 1980s, due to the rapid development of large integrated circuits (IC), power electronics, and advanced control technologies, more sophisticated and complex motor control functions could be realized via microprocessors or digital signal processors. Furthermore, induction motor application scopes were not only further extended to the stepless realm but also capable of excellent synchronization positioning functions applied in a variety of servo systems.

After the Kyoto Protocol was adopted in 1997 and implemented in 2005, the agreement signatories had to formulate domestic energy efficiency standards and regulations to facilitate the promotion of carbon reduction strategies to achieve the corresponding carbon reduction targets. In a variety of energy-saving regulations and policies, due to its widespread usage, the motor is regarded as a device with the largest energy-saving potential. Hence, several minimum motor energy efficiency standards were launched. Furthermore, there is a trend for both the standard level and the implementation scope to be upgraded phase by phase.

From the investigative data, the electricity consumed by the motors accounts for more than half of the total electricity use, specifically 70% of the power consumed in the industrial sector [17]. Therefore, for several applications, the high-efficiency motor technology plays a pivotal role in the conservation of the effective energy. Currently, most of the developed countries have designated an energy efficiency labeling system as not only an important strategic tool for promoting energy-efficient equipment or appliances but also a mandatory rule for vendors to reveal energy efficiency information on products. Consumers are stimulated by these incentives to purchase high-energy efficient products; thus, the national carbon reduction policy objectives may be achieved.

For example, motors used in industrial applications particularly account for the larger portion (approximately 64%) of electricity consumption by all electric motors across sectors in the US [18]. This statistic created a powerful incentive to accelerate the development of higher efficiency motors. Various methods to improve efficiency are to use thinner steel laminations in the stator and rotor core, use steel with better electromagnetic properties, add more steel, increase the wire volume in the stator, improve the rotor slot design and insulation, and use smaller, more efficient fans. These innovations result in a higher-priced motor; thus, companies must consider offering a separate line of high-efficiency motors to its customers along with the conventional ones [19]. The factors to be considered by a firm on whether to purchase a high-efficiency motor were discussed, i.e., starting torque, acceleration, horsepower, duty cycle, motor environment, efficiency, power, factor, and initial cost [20].

The global market demand for high-efficiency motors is increasing each year. In 2010, IE2 was implemented in the EU and China, making IE2 a common energy efficiency standard in key countries. The countries currently setting IE2 as the minimum energy efficiency standard (MEPS) include USA, Canada, South Korea, Australia, New Zealand, EU and China. The total annual industrial motor consumption in these countries accounts for approximately 60% of the global total. In other words, at least 60% of the overall motor market uses IE2 as the minimum purchase standard.

Furthermore, during 2010–2011, the IE3 standard was executed in the United States and Canada, thus enhancing the IE3 motor market demand up to 25%. Because of the general use of high-efficiency motors in these key countries, the forecasted proportion of the global IE2 and IE3 high-efficiency motors substantially increased from 42% in 2010 to 78% in 2014, hence significantly driving the business demand and opportunities for high-efficiency motors and their key components.

The EU has announced that the minimum motor energy efficiency standards will be raised to the IE3 level between 2015 and 2017, which indicates that after 3–5 years, the market demand for IE3 motors will be increased by at least 25%. Furthermore, due to the expectation that China will follow the EU's lead to implement the IE3 standard, it is estimated that after five years, the IE3 motor market demand will grow up to 60% in the overall market.

Because the costs of an induction motor and a permanent magnet motor are similar, when considering the compliance with the IE3 efficiency standard, the permanent magnet motor is expected to fully replace the low-voltage induction motor with its superior advantages of size, speed, load and other features to become the market mainstream in countries where the IE3 is implemented as a minimum energy efficiency standard. The primary products of permanent magnet motors include permanent magnet synchronous motors and brushless DC motors (BLDC). In recent years, permanent magnet motors have been widely used in inverter fans, compressors, machine tools, electric vehicles, and power steering to replace traditional induction motors. A brushless DC motor is representative of today's high-efficiency motors and a rising star of the motor industry due to its high efficiency, low power consumption, long life, no noise, virtually no maintenance and more precise control of torque compared to a DC brush motor; however, the disadvantages are that at low speeds, the control is still unstable, the price is more expensive, and a drive controller is needed.

In recent years, energy-saving motors have become the international focus for addressing climate change issues and meeting carbon reduction targets based on the Kyoto Protocol agreement. Switching to high-efficiency motors, variable frequency control technologies, and motor system energy management are common practices implemented by major countries. However, the greatest obstacle for promoting energy-saving motors is the decision-making mode to perform system management, i.e., how to make users purchase high-efficiency energy-saving products. Experiences demonstrate that countries cannot rely on cost-benefit analyses to expect the market to switch to high-efficiency motors automatically. Only policy incentives and regulatory environments are capable of changing the market demand, which is not only true for the domestic market but also for international trades.

The current global motor efficiency standards are in a transition state. Therefore, there are several motor manufacturers who are uncertain on how to respond to future demands. The proposed recommendations are that the industry must prepare by setting short- and medium-term goals for the production of energy-saving motors already regulated in the EU, Japan, United States and other developed countries, thus turning crises into opportunities. The emerging countries' demand potentials are enormous, such as China and India, which can be considered as a long-term market target. Additionally, the peripheral key component factories must work harder to develop high-performance components, including motor cores and permanent magnets.

3. International and domestic promotion polices

As listed in Tables 1, 2 and 3, since 1990, major countries have formulated several energy efficiency standards to improve the motor energy efficiency. The standards are implemented and reviewed phase by phase. Furthermore, all of the imported or sold motors are required to comply with the high-efficiency standards. The purpose is to improve the industrial energy use as efficiently as possible to increase national industrial competitiveness and enhance R&D capabilities and manufacturing technologies for high-efficiency motors; thus, the '3E' objectives of economic prosperousness, environmental protection, and energy conservation can be achieved simultaneously.

Table 1
Global industrial motor-related promoting schedule.
Sources: [21].

State/region	Introduction schedule	Norm level	Applicable norm
Japan	2015	IE3	-
US	2010/12	IE3	NEMA MG1-12-12
Canada	2011/1	IE3	CSA C390
Mexico	2011/1	IE3	NOM-016-ENER-2010
EU	2011/6 2015	IE2 IE3	IEC60034-30(2008)
South Korea	2010/7	IE2	KS C 4202
China	2011/7	IE2	GB18613-2006
New Zealand/ Australia	2006	IE2	MEPS
Taiwan	2013/6-2014/6 2014/7-2016/6	≧IE2 ≧IE3	CNS 14400

3.1. United States

In 1992, the United States enacted the Energy Act (EPAct), which regulated that the low voltage three-phase induction motors imported into the United States after 24 October 1997 with a capacity below 200 HP had to comply with the performance standards provided in the Act. Furthermore, in 2003, based on existing law, the United States re-examined the motor performance management to formulate the NEMA Premium® standards, in which the motor efficiencies were 1 to 2% higher than that of the EPAct average and the motor specification and capacity range were expanded to 500 HP. The motors that conformed to the standard could be labeled with a NEMA Premium® logo. Since December 2010, the United States has implemented the NEMA Premium® standard, which is equivalent to the IE3 standard level.

3.2. European Union

Additionally, the EU considered the importance of energy-efficient motors; thus, the CEMEP (European Committee of Manufacturers of Electrical Machines and Power Electronics) followed in the footsteps of the United States. In 1999, the existing motors' energy efficiencies were clearly defined into three levels: eff1, eff2, eff3. A motor with an efficiency between eff1 and eff2 is classified as a general motor (IE1). If the efficiency is higher than eff1, then it is a high-efficiency motor (IE2). Lastly, if the efficiency is lower than eff3, then it belongs to a pre-specification (IEC 60034-1). The European Union implements these three levels to regulate all of the motor energy efficiencies in Europe.

In the promotion of high-efficiency motors standards (IE2), the EU system is divided into several stages for implementation; thus, its schedule is behind that of the United States, Canada, Australia, New Zealand and other countries. The provisions of the EuP (Energy-using Product) Directive can be given as follows. A motor with power in the range of 0.75–375 kW should comply with the IE2 standard from 2011/6 onwards. A motor with power in the range of 7.5–375 kW should comply with the IE3 standard (or IE2 plus inverter operation) from 2015/1 onwards. A motor with a full range of 0.75–375 kW should comply with the IE3 standard (or IE2 plus inverter operation) from 2017/1 onwards. To be sold in the EU,

Table 2
International motor efficiency standards.
Source: [22].

Motor efficiency level	IEC 60034-30	United States (DOE/NEMA)	European Union (CEMEP)	Japan	Taiwan	China
Premium	IE3	Premium (NEMA2002)	–	–	–	1st Level
High Efficiency	IE2	EPAct (DOE1997)、(Australia, New Zealand MEPS-2006)	eff1(1999)	JIS-C4212 (2000)	CNS 14400 (2012)	2nd Level
Standard	IE1	(Australia, New Zealand MEPS-2002)	eff2(1999)	–	CNS 2934	3rd Level
Preliminary specification	IEC 60034-1	–	eff3(1999)	–	–	–

Note 1: Canada and Mexico use the U.S. standard.
Note 2: The so-called 'IE' refers to International Energy-efficiency Class.

Table 3
Ranges specified by international motor efficiency standards.
Source: [23].

State/Region	Voltage/frequency	Power range	Level range	Specification	Minimum equivalent performance
Taiwan	< 600 V ± 10%, 60 Hz	0.37–200 kW	2–8	CNS14400 high-efficiency motor	CNS 14400 includes three levels: IE+, IE2, IE3.
Japan	< 1000 V ± 10%, 50/60 Hz	0.75–375 kW	2–6	JIS C4034-30/2011	Enhancing to IE2 based on IEC60034-30.
China	< 1000 V ± 10%, 50 Hz	0.55–315 kW	2–6	GB 18613 Level 2(2011); Level 3(2008)	Level 2 from 2011/7/1-equivalent to IE3 (mandatory standard); Level 1 from 2016/7/1-equivalent to IE4.
European Union	< 690 V	0.75–375 kW	2–6	EC, Lot11/2009	2011/6/16-IE2; 2015/1/1-IE3-7.5-375 kW (or IE2 with inverter); 2017/1/1-IE3-0.75-375 kW (or IE3 with inverter).
United States	< 460 V ± 10%, 60 Hz	1–200 hp	2–6	NEMA EPAct EISA 2007	2010/12/19-IE3 for horizontal type, IE2 for vertical type.

Table 4
Category of inverter application markets.
Sources: [23]

Category	Motor power (kW)	Application field
Low voltage	≤ 7.5	Appliance product
Middle voltage	11–30	Electric vehicle drive
Middle high voltage	37–90	Electric vehicle drive
High voltage	≥ 110	Wind turbine

motors must meet the above scheduled requirements and criteria, thus aiming to ensure the motor energy efficiency continue with international trends.

3.3. *Japan*

JIS C 4212, which was formulated in 2000, was used as Japan's high-efficiency induction motor specification (IE2). Qualified products have been sold in the market for over a decade. However, the annual domestic shipment of Japanese high-efficiency motors (IE2) accounts for only approximately 1% of the total induction motors sold in the market. The fundamental reasons are that (1) the initial cost for introducing a high-efficiency induction motor is 20–30% higher than that of the standard induction motor; and (2) in Japan, for high-efficiency motor technology, the installation of an inverter in the motor is a common practice that can improve the overall efficiency more effectively to further achieve the energy-saving targets, as depicted in Table 4. However, in the worldwide trend of actively promoting high-efficiency motors and considering broadening foreign trade, Japan set 2015 as the target year to begin the implementation of the IE3, similar to the EU. A detailed plan to introduce the IE3 specification was announced in 2012 [24].

3.4. *Taiwan*

In 2003, Taiwan announced CNS 14400 as the national high-efficiency motor standard (IE2). The revised version was introduced in 2012, in which commercially available monomer motors were also included in the energy efficiency management laws. Furthermore, to accelerate the use of high-efficiency products to replace existing energy-intensive motors, the Taiwanese government proposed a "Comprehensive Innovative Motor Promotion Plan" in 2013/5 [25]. The plan was comprised of two phases: (1) the first phase, from an approved date to 2014/6, executed the promotion of high-efficiency motors with an IE2 level or higher (including IE3); and (2) the second phase, from 1 July 2014 to 30 June 2016, executed the promotion of high-efficiency motors with an IE3 level or higher. According to the estimation of BOE MOEA, the total sales of the IE2 and IE3 motors in the first phase should be greater than 10,000 kilowatts (kW). The total promotion capacity in three years will be 600 MW. The subsidy rates are (1) 100 NT$/kW for the IE2 motor and (2) 300 NT$/kW for the IE3 motor. The total subsidy in the first phase is 60 million NT$. The entire three-year total funding is 180 million NT$.

Based on an evaluation by the Ministry of Economic Affairs, the total electricity savings will be 120 GWhs over the scheduled three years and an annual electricity savings of 54 GWhs in each subsequent year. The Ministry of Economic Affairs emphasized that domestic motor manufacturers and agents have to fulfill the annual total sale requirement of 10,000 kW before they can receive the subsidies. Furthermore, it is estimated that the demonstration subsidy program could create a motor output value of 1.56 billion NT$, accelerate the upgrade of the domestic motor in the manufacturing of the IE3 motor technology, drive the associated motor machinery industry output of approximately 5 billion NT$, and enhance the export value [25].

As shown in Table 5, in 2011, Taiwan produced approximately 100 million motors with a total output value of 21 billion NT$ [23]. However, conditions have not yet been restored to levels prior to the global financial crisis. Primarily, Taiwan's motor industry has a complete supply and manufacturing chain, including high, middle and low streams. In Taiwan, although the motor industrial operation modes have different approaches, the results achieved are the same as other IT industries.

The emerging issues of energy savings and carbon reductions have led to the rapid development and popularization of high-

Table 5
Production and output of electric motors in Taiwan.
Source: [26–29].

	Production (million unit)		Output (billion NT$)		Total output (billion NT$)	Import value (billion NT$)	Export value (billion NT$)	Domestic demand (billion NT$)
	Motor	Micro (small motor)	Motor	Micro (small) motor				
2007	7.424	107,891	18.19	5.12	23.30	10.01	15.16	18.15
2008	6.774	103,355	17.73	4.88	22.61	11.89	15.30	19.20
2009	4.911	84,327	11.81	3.93	15.74	8.11	13.21	10.64
2010	7.204	107,870	16.56	4.82	21.38	14.57	16.54	19.41
2011	6.456	100,922	16.25	4.71	20.96	17.14	19.36	18.74

efficiency motors. Traditional motor manufacturers can make the best of this situation by actively transforming themselves to seize tremendous business opportunities.

3.5. Other countries

The promotion of high-efficiency motors in other countries can be described as follows:

(1) Korea: From 2010/7, to maintain compliance with IE2, Korea began implementing high-efficiency motor specification.
(2) Mexico, Canada: From 2011/1, Mexico and Canada implemented premium IE3 motors.
(3) China: from 2011/7, China began to implement IE2 high-efficiency motors.

4. International motor efficiency test specifications

In the past, the various test standards and methods set for induction motors around the world were quite different, thus resulting in the measured efficiency values having a difference of a few percentage points. To improve and reconcile the different test standards and methods, the EU completed the compilation of a new standard, known as IEC60034-30: 2008. The original efficiency standards eff1 and eff2 have been replaced by IE2 and IE1, as indicated in Fig. 3.

In recent years, the international community has actively taken relevant measures to prevent the occurrence of global warming, in which induction motors consuming 40 to 50% of global total energy use are required to pursue the goal of high efficiency [29]. Generally, motor efficiency losses are divided into several categories: primary copper loss, secondary copper loss, iron loss, mechanical loss, slip loss, etc. Using core shape optimization and material upgrades, motor monomers can be promoted to high-efficiency induction motors, for which the efficiency loss can be reduced by 20% compared to standard motors. Thus, motor manufacturers have introduced high-efficiency induction motors with efficiencies equivalent to the international benchmark efficiencies IE2 (High Efficiency) and IE3 (Premium).

In the induction motor, efficiency (heat) loss is caused by the current passing through the rotor conductor while in the permanent magnet motor, the rotor conductor part is composed of a permanent magnet. Therefore, in the IPM (Interior Permanent Magnet) motor, when the permanent magnet is used to rotate the rotor part, there is no loss (heat) caused by the secondary current or slip, hence resulting in a higher efficiency. Furthermore, in the IPM motor, because the rotor size is smaller than that of the induction motor, miniaturization and a lower weight can be realized. Thus, in recent years, manufacturers have introduced the IPM motor with an efficiency equivalent to the international efficiency benchmarks IE3 (premium) and IE4 (super premium). The efficiency of high-efficiency motors (IE2) is approximately 3–5% higher than that of average motor. In short, using the high-efficiency motor more frequently will result in greater energy savings. Hence, the adoption of high-efficiency motor equates to saving money and electricity, as indicated in Table 6.

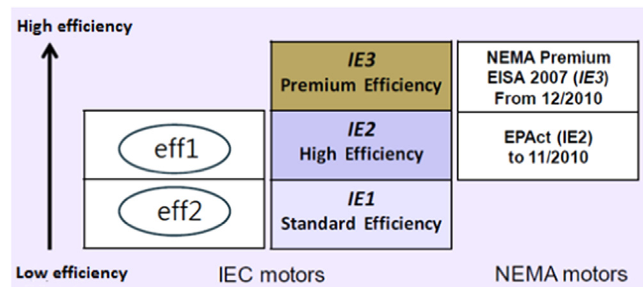

Fig. 3. Motor efficiency standards comparison between the EU and the North American.
Sources: [23].

Table 6
Comparison between a high-efficiency motor and a standard motor (50 hp).
Source: [30].

	Standard motor	High-efficiency motor	Cost gap (NT $)
Purchase cost (NT$)	28,540	34,280	5708
Efficiency (%)	89.5	93.6	–
Power cost during 20 years running (NT$)	1,915,700	1,831,720	−83,980

Currently, the motor testing methods used by each country are not similar; thus, the efficiency values have to be harmonized before they can be compared. Table 7 lists the motor testing methods used by the major countries in the world.

5. International motor efficiency normative contents

To ensure the effective promotion of high-efficiency motors, key countries have formulated relevant efficiency standards. Except for the United States, Canada, Australia and New Zealand, who have adopted mandatory standards, other countries continue to use voluntary standards. In Fig. 4, as exemplified by 50 Hz, 4-pole induction motors, the motor efficiencies (%) increase proportionally to the capacity values (kW). Additionally, the international motor standard comparisons between IEC (IE1, IE2, and IE3) and CEMEP (eff1 and eff2) are illustrated.

5.1. United States

After the first energy crisis in the early 1970s, U.S. motor manufacturers, such as GE, launched a series of high-efficiency products in 1989. This was the first high-efficiency induction motor efficiency standard developed by the National Electrical Manufacturers

Table 7
International motor efficiency test specifications.
Source: [31].

Test method	State	Applicable norms	Note
Dynamic measurement	US	IEEE-112A	Output torque measurement
Loss separation method	Taiwan	CNS 10919	Measuring mechanical and resistance losses; and estimating electromagnetic and miscellaneous losses
	US	IEEE-112B	
	Canada	CSA-C390	
	Australia, NZ	AS/NZS 1359	
	International	IEC61972-Method-1	
	Japan	JIS C4212	
Fixed loss method	International	IEC60034-2	IEC 60034-2: Miscellaneous loss = 0.5% Input; and IEC 61972: Miscellaneous loss = 1.5–3.0% Input
	UK	BS-269	
	International	IEC61972-Method-2	
Mapping method	Japan	JEC-37	Miscellaneous loss = 0

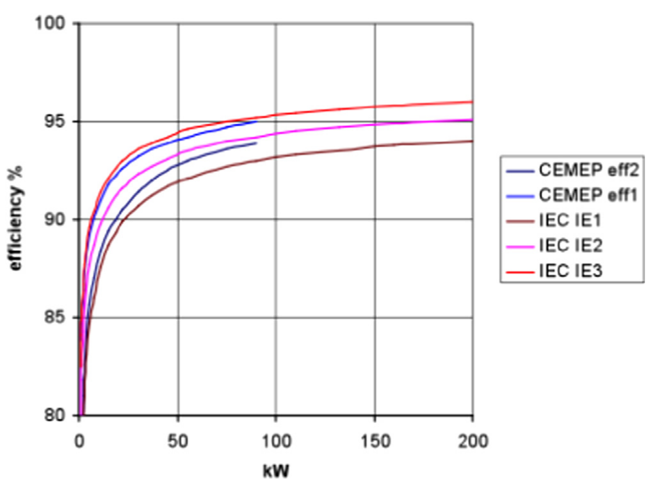

Fig. 4. Motor efficiencies according to different capacity values (50 Hz, 4-pole). *Source:* [32] High.

Association (NEMA), i.e., NEMA12-9. To accelerate the popularization and application of high-efficiency induction motors, the U.S. Congress passed an amendment of the "Energy Policy and Energy Conservation Act" in 1992. The so-called EPAct stipulated that any motor produced in or exported to the United States had to meet the high-efficiency motor standards. A five-year transitional period was provided to the Act, which was eventually implemented on 24 October 1997. The motor minimum efficiency standards prescribed by the U.S. Energy Policy Act (EPAct) are described in Table 8.

In recent years, because the U.S. electricity supply remains limited, a series of ultra-efficient motors have emerged in the United States market. Therefore, in 2001, NEMA joined state power companies to organize a Consortium for Energy Efficiency (CEE) to develop a new ultra-efficient motor standard, known as NEMA Premium (equivalent to IE3). The motor start performance required by the standard is consistent with the EPAct. Furthermore, the NEMA Standard MGI-2003 prescribed two NEMA Premium efficiency indicators, i.e., NEMA12-12 and NEMA12-13, which correspond to motors below 600 V and medium voltage motors at or below 500 V, respectively. The new indicators essentially correspond to the ultra-efficient motor average in the U.S. market.

As can be seen in Table 9, there is a 4-level fully sealed motor efficiency comparison between the NEMA Premium and the EPAct, in

Table 8
Comparison between the EPAct efficiency standards and the general industrial motor efficiency averages.
Source: [33].

Power (hp)	EPAct efficiency (%)	General industrial motor efficiency (%)	Depletion decreased value* (%)
1	82.5	76.8	24.6
2	84	81.1	15.4
3	87.5	81.4	32.8
5	87.5	83.9	22.4
7.5	89.5	86.4	22.8
10	89.5	86.4	22.8
25	92.4	87.7	27.2
50	93	91.5	17.7
75	94	92.1	24.1
100	94.5	91.9	32.1
200	95	94	16.7
Average	89.95	87.25	24.3

* The motor energy depletion decreased value.

Table 9
The efficiency comparison between the NEMA Premium and the EPAct.
Source: [33].

Power (hp)	NEMA Premium (%)	EPAct Efficiency (%)	Depletion decreased value* (%)
1	85.5	82.5	17.1
2	86.5	84	15.6
3	89.5	87.5	16.0
5	89.5	87.5	16.0
7.5	91.7	89.5	21.0
10	91.7	89.5	21.0
25	93.6	92.4	14.7
50	94.5	93	21.4
75	95.4	94	23.3
100	95.4	94.5	16.4
200	96.2	95	24.0
Average	91.27	89.95	18.8

* The motor energy depletion decreased value.

which the NEMA Premium has an efficiency improvement of 1–3% compared to that of the EPAct. Currently, the NEMA Premium is often used as a referential standard for subsidies when power companies encourage users to buy ultra-efficient motors. The NEMA Premium motor is recommended for use on occasions where the motor would be operated more than 2000 h per year and the load is higher than 75%. The U.S. first class motor (1–200 hp) minimum load factor efficiency standards can be observed in Table 9.

5.2. European Union

After the establishment of the European Union in 1993, the EU performed policy, market surveys and research on the energy savings potential of high-efficiency motors and, for the first time, launched motor performance indicators (i.e., EU–CEMEP Agreement) in 1999. Furthermore, in terms of motor applications, a high-efficiency motor database (i.e., Euro DEEM) was established. The EU–CEMEP agreement reached by both the EU and the CEMEP was used to grade and label the motors' efficiencies by stipulating two levels (i.e., high and low). In other words, if a product's efficiency is lower than the low level, it was called an eff3 motor whereas if it was between the low and high levels, it was called an eff2 motor. Furthermore, if it was higher than the high level, it was classified as an eff1 motor (equivalent to IE2). Specifically, the loss decrease rate of the eff1 motor decreased 40% compared with that of the eff2 motor whereas the loss decrease rate of the eff2 motor decreased 40% compared with the eff3 motor. Generally, the efficiency increase rate of the eff1 motor increased 1–5% compared with that of the eff2 motor.

As estimated by the CEMEP, if all of the current eff3 motors were replaced by the eff2 motors, there would be 6 TWhs of electricity saved each year, which is equivalent to a savings of 300 million Euros in electricity costs at an electricity price of 0.05 euro/kWh. The agreement provides that the motor efficiency value and level should be listed on the nameplate and sample, thus facilitating the selection and identification by users. After a contract is voluntarily signed by the CEMEP member or unit, the EU–CEMEP agreement is then executed, in which the non-member manufacturers, importers and retailers are also welcome to participate. Thus far, there are 36 participating manufacturers accounting for 80% of all European motor output.

On 31 October 2009, the EU formally announced the expansion of the original "EuP Directive (2005/32/EC)" into the "Energy-related Products (ErP) Eco-design Directive (2009/125/EC, ErP)". The new directive covers nearly all energy-related products using product eco-design requirements that indirectly affect the energy use, reducing energy consumption and greenhouse gas emissions, and facilitating the development of the national and social sustainable management. Although the EuP Directive is replaced by the ErP Directive, the change only limits the scope of architecture. Furthermore, the EU continues to conduct early studies on various products to develop more appropriate eco-design requirements and implementation methods. The EU has already announced the eco-design implementation methods for nine products.

5.3. *Japan*

Japan's high-efficiency motor standard JIS-C4212 (2000) is an efficiency requirement for a three-phase squirrel cage induction motor with operational frequencies of 50 Hz and 60 Hz. The specifications of the motors suitable for the standard can be given as follows: (1) the rated voltages are less than 1000 V; (2) the rated output powers are between 0.75 kW and 375 kW; and (3) the specified motors are actuation and gear motors in two, four, and six levels. This standard is not applicable to the combination of inverters and machinery (such as pumps, compressors and fans) because the motors cannot be tested separately from the machinery.

The motor efficiency calculation is based on three rated factors: output power, frequency and voltage. Furthermore, both the efficiency and loss are calculated using the JIS C4034-2-1. If the motor is used over a wide voltage range, regardless of the voltage's fluctuating magnitude, the specified rated voltages should correspond to the specified efficiencies and efficiency levels (i.e., IE-code). In terms of materials, based on the changes in the manufacturing engineering and testing procedures, different motors with different efficiencies may be produced. Therefore, if different efficiencies are generated due to different outputs, it is forbidden to use just one value; multiple values should be considered. Thus, in this standard, the rated output efficiency is known as a nominal efficiency.

5.4. *China*

In January 2002, the Chinese government formally introduced the "Minimum Performance Value and Energy-saving Evaluation Standard for Small and Medium Three-phase Asynchronous Motor", i.e., GB18613-2002. This standard provided two sets of motor efficiency indicators: (1) minimum performance efficiencies, serving as mandatory benchmarks; and (2) energy-saving efficiencies, serving as recommended indicators. The former is the average efficiency of all motors produced in China while the latter is 2–3% more efficient than the former. Afterwards, the Chinese government stipulated that all of the basic motor technical requirements should be in accordance with the IEC standards. Therefore, the EU–CEMEP eff2 indicators became Chinese motor minimum performance standards while the EU–CEMEP eff1 indicators (i.e., 90.05% average efficiency) served as the Chinese recommended motor energy-efficient benchmarks [34].

Due to sustained economic development, the output of the AC motor has increased rapidly in recent years. Additionally, the high-efficiency motors currently produced in China are primarily for exportation. Moreover, with the continuous development of China's economy, the energy supply has become more limited. Thus, in June 2005, there was a revision aimed at the GB18613 standard. Furthermore, in August 2006, the Chinese government released the GB18613-2006 standard. Then, the National Development and Reform Commission, AQSIQ, and the State Certification and Accreditation Administration Committee jointly issued "The People's Republic of China Implementing Energy Efficiency Labeling Product Catalog (3rd Edition)" on January 18, 2008, in which the imported small and medium three-phase asynchronous motors had to be attached with energy efficiency labels. The energy efficiency labeling is based on the "GB18613 Small and Medium Three-phase Asynchronous Motor Minimum Performance Values and Levels" standard. Additionally, the Chinese government approved the "National Standard of Minimum Performance Values and Levels for Small Power Motors", which had been implemented before the end of 2011.

In addition to mandatory energy efficiency labeling, the Chinese government also promoted energy-saving logos, which was a voluntary certification system. On June 2, 2010, the Ministry of Finance and the National Development and Reform Commission jointly launched the "The Details of Energy-saving Products Beneficial to Promote the Implementation of High-efficiency Motors", which incorporated efficient motors into the scope of energy-saving products. Furthermore, financial subsidies were given to those promoting efficient motors. There are three types of subsidy rates: (1) 15–40 Renminbi/kW, which was designated for low-voltage three-phase asynchronous motors with energy efficiency ratings of 1st and 2nd levels; (2) 12 Renminbi/kW, which was formulated for high-voltage three-phase asynchronous motors; and (3) 40–60 Renminbi/kW, which was specified for rare earth permanent magnet motors. The enormous financial incentives along with the direct subsidies given to motor manufacturers are more conducive to promoting and accelerating the high-efficiency motor market in China.

GB18613-2006 is applicable to motors with the following specifications: (1) voltages below 690 V; (2) 50 Hz three-phase AC; (3) energy efficiencies of 2nd and 3rd levels and rated power of 0.55–315 kW; (4) energy efficiency of 1st level and rated power of 3–315 kW; (5) levels 2, 4 and 6; (6) single-speed enclosed fan-cooled motors; and (7) N designed general purpose motors or general purpose explosion-proof motors. Moreover, GB18613-2006 divides the motor energy efficiencies into three categories: 1st level, 2nd level, and 3rd level, in which the 1st level is the highest. Originally, the efficiencies of all motors should not be lower than the 3rd level with a rated output power and a 75% rated output power. However, after the standards have been implemented for four years, i.e., after June 30, 2011, the efficiencies of all motors should not be lower than the 2nd level. Based on the provisions of GB18613-2006, the motor efficiency should be determined by the loss analysis methods described in GB/T1032, where the miscellaneous losses are evaluated as 0.5% of the rated input power.

5.5. *Taiwan*

In 2003, following the U.S. standards specifically for 60 Hz three-phase induction motors below 600 V, the Taiwanese government introduced the CNS14400 standard, commonly known as the "Taiwan High Efficiency Motor Standards." However, this standard is currently only a referential law regarded by the domestic industry.

The CNS14400 had not been revised since 2003. During this period, the international high-efficiency motor standards have been upgraded continuously. Moreover, the diverse international standards are not conducive to international motor trades. Thus, the International Electrotechnical Commission (IEC) reconciled several standards developed by countries to formulate IEC60034-30: 2008, which is an efficiency standard set for three-phase squirrel cage induction motors. In reference to IEC60034-30, the Taiwanese government introduced the revised edition of the CNS14400 standard on March 26, 2012.

The revised CNS14400 is applicable for low-voltage three-phase squirrel cage induction motors with rated frequencies of 60 Hz and 50/60 Hz, rated voltage of 600 V or less, and ambient temperature below 40 °C but not submerged electric motors, integrated units and inseparable drive facilities, multi-speed motors, and exceptions recognized by other national standards.

Compared to CNS14400: 2003, the new standard divides high-efficiency induction motors into three categories: (1) IE1+ for high efficiency; (2) IE2 for premium efficiency; and (3) IE3 for ultra-high efficiency. In other words, IE1+ is equivalent to the high-efficiency induction motor efficiency defined in 2003, i.e., IE3 > IE2 > IE1+. Compared to IE1, IE2, and IE3 defined by the IEC 60034-30, CNS14400 IE1+ is between IE1 and IE2 of the IEC 60034-30 while both IE2 and IE3 are similar.

In the future, there will be several ways to identify a high-efficiency motor: high-efficiency motor nameplate, rated efficiency, and IE labeling. In other words, motors produced before the implementation of CNS14400 only have the rated efficiency label but no high-efficiency motor nameplate. Motors that comply with CNS14400: 2003 have a high-efficiency motor nameplate and a rated efficiency label. Lastly, motors that comply with CNS14400: 2012, except for a high-efficiency motor nameplate, are additionally labeled with the IE levels, such as IE1+, IE2, and IE3.

6. Suggestions

6.1. Industrial development strategies at design stage

Although its development is a rising industry trend, it is difficult for manufacturers and users to accept high-efficiency motors due to their high cost and price. In recent years, due to the rising costs of raw materials and labor, the industry faces tremendous pressure to control product costs and yields. We suggest that the industry should consider the following development strategies in the design stage:

(a) Automated motor assembly equipment: by developing motor automated production equipment, improving motor production efficiency, and augmenting production scale, the production costs can be reduced.
(b) Material-saving motor structure design: the motor core stamping industry could cooperate with the motor industry to develop a new type of motor structure featuring a material saving design; for example, applying a split-core as a convenient operation to winding operations along with modular assembly design, thus effectively reducing the materials, molds and post-process processing costs.
(c) Commonly shared kit drive module: although the efficiency of the DC brushless motor is high, the relative cost of its drive control module is expensive; hence, the industry should develop a shared set driver module using mass production and common applications, thus effectively reducing the driving control cost.
(d) Improving motor winding manner: changing the traditional cross-slot winding to single slot winding not only makes winding easier but also enhances the efficiency and reduces copper consumption; the row-wise winding method designed for the servo motor should be introduced to upgrade the single winding technology so that the copper can be wound in a more neat manner and with less vacancy. Furthermore, the single-slot winding machine is cheaper than the cross-slot winding machine, thus reducing costs.

6.2. The DC brushless motor is the most popular product in today's motor industry

In terms of the DC brushless motor, the R&D goals that have to be achieved by the motor manufacturers in the down, middle, and upper streams are motor design optimization, electromagnetic improvement of the silicon steel sheet, magnetic field characteristic enhancement of the permanent magnet, winding technology improvement, and sophisticated electronic control technology. Additionally, to address the technical gaps faced by the industry, the capabilities of the industry, government and academia must be integrated together to develop relative technologies and key components, such as system design and integrated-and-matching technologies, motor professional training, critical materials, process automation, drive control, and testing verification.

6.3. System design and integration technology

Due to a lack of integration in both the IC and motor industries in Taiwan, when focusing on motor production, the motor industry is unable to grasp the key motor drive control components. Thus, it is difficult to meet the demand required by the industry, i.e., to develop appropriate motor products in line with the needs of the application industry. Therefore, integrating the semiconductor industry, which already possesses a competitive advantage, and the motor industry to jointly develop a drive control system is an excellent opportunity for Taiwan to upgrade their overall industry structure [35].

Taiwan has a complete motor unit design capability in its academia, including MSRL and GEL in ITRI, NCKU motor center, MIDRC, electrical engineering departments in Taiwan Tech and Taipei Tech, and the NTU motor center [36,37]. Enterprise Alliance is also a viable approach. Through a combination of different technologies, successfully developed shared drive control modules can be commonly used by a variety of different motors and consumer products, thus resulting in the benefits of reduced costs, design-fee savings, and easy purchasing. The successful combination of motor design and control not only shortens the trial period but also reduces the investment in labor and equipment, thus enhancing competitiveness.

6.4. Key material technology

Highly magnetic thin silicon steel sheets with low core loss are an indispensable material in manufacturing high-efficiency motors. China Steel has invested in the development of key material technology, including thin silicon steel sheets of less than 0.25 mm, no/less rare earth metal magnets, magnet magnetization alignment technology, high conductivity magnetic amorphous alloys (metal magnetic material with lowest iron loss) and composite soft magnetic materials. Government policy should lead industries, academia, and institutes into upgrading key materials. The development of basic material technology can be included in governmental R&D projects, thus boosting the upgrade of overall high-efficiency motor technology.

Taiwan lacks natural resources. Therefore, the development of material technology for the no/less rare earth motor is necessary for the Taiwanese motor industry to avoid relying on critical materials. Taiwan and Japan can join as strategic alliances in technical co-production, expanding the business opportunities of permanent magnet motors featuring high performance, low cost, and heat resistance.

Table 10
Domestic and foreign implementing aspect comparisons.

Industrial energy-saving measures (A case study of high-efficiency motors)

Aspect	Domestic	Foreign
Policy	• In June 2013, MOEA launched a "High-efficiency Motor Demonstration Promotion Subsidy Program" totaling 3 years, 2 phases. • First phase (from approved date to 30 June 2014): promote motor energy efficiency above IE2 level (including IE3). • Second phase (1 July 2014 to 30 June 2016): promote motor energy efficiency above IE3 level. • In 3 years, a promotion capacity of 600 MW is targeted, with subsidy rates of 100 NT$/kW (IE2) and 300 NT$/kW (IE3). The total subsidy expenditure is approximately 60 million NT$. • Expect approximately 1.56 billion NT$ of motor output value and create approximately 5 billion NT$ of relative industrial production value. The program will expire after 2016, and there will be a total electricity savings of approximately 120 GWh and a continuously annual electricity savings of approximately 54 GWh afterwards.	• At the end of 2010, the United States implemented the NEMA (National Electrical Manufacturers Association) standard, which was approximately equivalent to IE3. Currently, the IE4 Super Premium is also emerging. • EU has regulated that the efficiency of the motor should not be less than IE2 after 16 June 2011, and IE3 is scheduled for phased implementation from 2015–2017.

Policy – Foreign (continued):

Nation/Region	Introduction schedule	Specification level	Applicable specifications
Japan	Scheduled in 2015	IE3	–
United States	December 2010	IE3	NEMA MG1-12–12
Canada	January 2011	IE3	CSA C390
Mexico	January 2011	IE3	NOM-016-ENER-2010
EU	June 2011	IE2	IEC60034-30 (2008)
	Scheduled in 2015	IE3	
Korea	July 2010	IE2	KS C 4202
China	July 2011	IE2	GB18613-2006
New Zealand/ Australia	2006	IE2	MEPS

Regulatory

Motor efficiency level	The International Electrotechnical Commission IEC 60034-30	United States DOE/NEMA	EU CEMEP	Japan	Taiwan	China
Premium	IE3	Premium (NEMA2002)	–	–	–	1st level
High efficiency	IE2	EPAct (DOE1997), (Australia and New Zealand MEPS-2006)	eff1 (1999)	JIS-C4212(2000)	CNS 14400 (2012)	2nd level
Standard	IE1	(Australia and New Zealand MEPS-2002)	eff2 (1999)	–	CNS 2934	3rd level
Preliminary specifications	IEC 60034-1	–	eff3 (1999)	–	–	–

Note 1: Canada and Mexico use the United States standard.
Note 2: The so-called 'IE' refers to the International Energy-efficiency Class.
Data source: (DIT, 2012)

Aspect	Domestic	Foreign
Market	• In 2011, the Taiwanese motor production was approximately 100 million units and worth approximately 21 billion NT$. In addition to two large enterprises Datong and TECO, the domestic manufacturers of industrial induction motors are small and medium enterprises. Datong and TECO combined account for 75–80% of the domestic motor market, where the majority is manufacturers of the industrial induction motor. • The domestic use of 60 Hz three-phase induction motor in 2001 was 0.59 million units and 0.533 million units in 2005.	• The global motor market grows steadily in recent years. The global electric motor sales market is estimated to be approximately USD 91.75 billion in 2015 and expected to grow at a compound annual growth rate of 6.38% during 2015–2020. • In recent years, the international community has actively taken significant measures to emigrate global warming. Wherein, the induction motor accounting for 40–50% of the world's total electricity consumption is the primary appliance required to fulfill the high-efficiency standards.

6.5. Drive control technology

A microprocessor is the hardware core in a motor drive control unit, in which the typical component is a vector control composed of power semiconductors, e.g., IGBT or MOSFET. For microprocessor control, the international R&D trends include a power input interface with active power factor correction, shared switch strategy between Pulse Amplitude Modulation (PAM) and Pulse Width Modulation (PWM), vector control methodology for motor output torque maximization and efficiency optimization, and integration design for both energy recovery and motor drive control. By integrating the semiconductor design and the manufacturing technology, it is possible to complement the drive control technology needed by the motor industry, thus building a complete industrial chain [35].

6.6. Testing and verification techniques

The current domestic motor energy efficiency standard (i.e., CNS14400: 2012) has been engaged with international standards. To promote the industry's continuous product improvement and push the technical level of the domestic motor industry, the active implementation of the new motor energy efficiency is a requirement for future Taiwanese motor industry products. Additionally, Taiwan should set up dedicated test units, which comply with the international norms of accredited laboratories [38].

7. Conclusions and policy implications

The global electric motor sales market is estimated to be approximately USD 91.75 billion in 2015 and expected to grow at a compound annual growth rate of 6.38% during 2015–2020 [16]. Industrial motors are an important energy consumption index. Most developed countries have implemented energy efficiency regulations similar to that of the European Union. For example, the United States has adopted the NEMA standard since the end of 2010. Currently, the Super Premium IE4 has also been formulated. The EU has clearly stipulated that the efficiency of motors listed for regulation should not be less than IE2 after 16 June 2011. Motors accounting for 40–50% of the total global electricity consumption become the major appliance requiring high-efficiency standards. Currently, the research and technical development of DC brushless motors is the most popular program in the motor industry. The other R&D items include the optimization of motor design, electromagnetic enhancement of silicon steel sheets, promotion of the advantages of permanent magnetic fields, modification of wire-winding technology and improvements in the electronic control technology. The emerging issues of energy savings and carbon reductions as well as the approach of the high-energy price era have led to the rapid development and popularization of high-efficiency motors.

The motor is the most energy-using component in the industry. Promoting the implementation of high-efficiency motors is not only conducive to boosting industrial competitiveness but also to reducing greenhouse gases. Thus, in recent years, several countries have addressed the enhancement of motor efficiency standards in their energy and industrial policies.

The aforementioned contents are summarized in Table 10. Wherein, through the three "policy, regulatory, and market" aspects, the differences between the domestic and foreign policies are compared to induce the policies that can be emulated by Taiwan for developing and promoting high-efficiency motors. The suggested policies for the development of the high-efficiency motors are not only applicable for Taiwan but also useful for other countries.

- To encourage manufacturers to apply for investments, the government should provide an investment-friendly environment, including the key support of hardware, software, and incentives.
- For the government to guide the direction of industrial development via policy and legislation, establishing market product specifications is the most direct, fast and effective method.
- Through policy incentives, the combination of various sources from academia and industry, integration of down-, middle-, and upstream-manufacturers, such as steel materials, permanent magnet, core stamping, motor winding machine manufacturers and motor assembly, etc., organization of joint R & D alliances and sharing research results will be doubly effective strategies.
- Referring to the current standards of developed or neighboring countries to establish rational and progressive motor efficiency standards, e.g., Japan, the European Union, and United States.
- The key component manufacturers can develop high-grade silicon steel, copper rotors, no/less rare earth permanent heat-resistant magnet motors, high power drives and electronic components for permanent magnet motors of low cost.
- Permanent magnet motors will become the mainstream market while brushless DC motors will be the future.

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