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Energy Performance Evaluation Method for Machining Systems Towards Energy Saving and Emission Reduction

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Abstract

Energy performance improvement is a basic significant way of addressing both energy security and environment concerns, which can promote energy-saving and emission-reduction. There are various measures of energy performance, with different purposes and applications. However, there are few models or approaches for measuring and quantifying energy saving potential in machining systems. To better perform the energy performance analysis and evaluating energy saving potential in machining, an energy performance evaluation method based on energy benchmark in machining systems is addressed. Energy performance characteristics is analysed, and some energy performance concepts and indicators are proposed. The energy performance evaluation based on energy benchmark is developed for machining systems. Furthermore, a case study involving the establishment of an energy performance evaluation and energy saving potential for gears in a real machining plant was examined, illustrating the practicability of the proposed method.

Keywords Energy saving · Emission reduction · Energy performance · Energy evaluation · Machining systems

1 Introduction

The consistent increase in the global demand for energy, the failure to provide this quantity, and the conditions for developing new energy sources have resulted in a dramatic increase in the cost of energy over past decades [1, 2, 3]. Investigation shows that global energy intensity fell by 1.8% in 2016. This recent trend of the decline was slowing down as depicted [4]. Although the Global Energy Intensity (GEI) in 2016 was lower than that in 2015, the average energy intensity was a significant increase compared to the preceding decades.

Currently, due to development of advanced technology, globally, energy efficiency has been 13% higher from 2000 to 2016 [4, 5]. Recent statistics reflect that there are larger differences in energy use with and without energy savings from efficiency improvements, and the global final energy use in 2016 improved by 12% without energy efficiency savings [6]. Therefore, improving energy efficiency is a very crucial and effective measure to solve the issues relating to energy supplies more urgent, especially for fossil fuels, and to relieve stress of GHG emissions, benefiting air quality and public health. Improving energy efficiency has become a crucial strategic target, which results in extensive interest in recent years [7, 8], especially in energy-intensive industries [9, 10]. The International Organization for Standardization [11], the European Union [12] and the Japanese Standards Association [13] implement numerous energy benchmarks and standards to support the energy-efficient production. The US Department of Energy has established special Industrial Assessment Centers providing effective measures to increase energy efficiency [14]. ISO 50,001 Energy Management Standard and the Europe 2020 Strategy were developed that aimed at achieving reduction of overall energy use [15].

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Recently, China jointly issued a series of national energy efficiency standards to provide important policy support [16].

To analyze and increase energy efficiency in the industry, barriers and the opportunities related to energy management and energy efficiency improvement have been carried out, i.e., energy efficiency measures, standards, labeling regulations, metrics and performance measurement on national and policy level [17–19]. Reddy analyzed barriers and drivers of energy efficiency based on a new taxonomical approach, which provided scope for appropriate policy interventions [20]. To investigate various barriers and the opportunities to energy efficiency improvement, some conceptual frameworks and models that show physical, technological, socioeconomic, economic, and market potential for environmentally sound technologies are proposed, which contributes to discussing some actions and measures of energy efficiency [21–23]. Besides, Bunse, et al. analyzed concepts and tools for measurement, control and improvement of energy efficiency in production management, and summarized ICT tools and standardization as important enablers for energy efficient manufacturing [24]. de Groot et al. identified the factors, determined by the investment behavior, and corresponding responsiveness of energy policies in nine different Dutch industrial sectors [25]. Ernst Worrell, et al. analyzed the sector-wide technologies and summarized process-specific technologies and measures focusing on energy-intensive industries [26]. Lo analyzed renewable energy and energy efficiency in electricity, industry, transportation, buildings, and local government, and identified limitations and room for improvement [27]. Wang, et al. addressed a method for measuring energy efficiency based on meta-frontier data envelopment analysis approach, and analyzed the source of energy inefficiency [28]. Lin, et al. investigated the technology gap of energy efficiency [29], and introduced an approach to measure energy efficiency [30]. Taylan, et al. presented an integrated decision model to analyze and improve energy efficiency processes in petrochemical industry [31]. Several solutions regarding energy efficiency for manufacturing have been offered [32].

Performance indicators as a key measure had been widely used to enable better monitoring and control of energy consumption to improve energy efficiency in industry [33]. The US Environmental Protection Agency proposed the ENERGY STAR and introduced the promoting indicators as an effective lever to measure energy-based performance [34]. Besides, Dietmair, et al. studied the energy consumption modeling and some approaches for improving energy efficiency performances in production processes [35]. Boydet et al. evaluated the energy performance indicator to develop the energy use benchmark in industrial plant [36]. Zhou, et al. proposed a performance indicator model of energy consumption allowance [37]. Cai, et al. widely studied the energy allowance and benchmark of the machining system and mechanical manufacturing industry [38], including the development of fine energy consumption allowance, multi-objective energy benchmark, dynamic energy benchmark [39], etc.

The U.S. Energy Information Administration published an energy yearbook in 2012 showing that energy consumption in the mechanical manufacturing industry accounted for 74.7% of the total energy consumption in the manufacturing industry [40]. Numerous surveys have indicated that the machining system consumes a large amount of energy, and the energy efficiency of the machining process is very low: usually less than 30% [41, 42]. With a wide distribution and large amount of energy consumption at a low efficiency, machining systems have considerable energy-saving potential [43]. It is therefore important to measure energy efficiency and energy potential of machining.

Based on an analysis of relevant literature, the pertinent literature revealed that industry production still lacked approaches and tools to better understand the energy efficiency behavior. The deficiencies focused mainly on that there were few effective methods for measuring energy efficiency and exploring energy potential, especially for the exploring energy potential of machining. Therefore, this study proposed a new concept of energy mining and the method realizing the energy efficiency measurement and energy potential exploration in machining. Meanwhile, the proposed energy mining can quantify energy efficiency of production and energy saving potential. Based on the tool, the superfluous energy can be controlled by the optimization method, and latent energy and energy efficiency can be found. Obviously, the energy mining was a crucial tool contributing to strengthening energy monitoring and management and improving energy efficiency, and to providing some helps in the process of policy-making, or for the evaluation of specific policy measures.

2 Materials and Method

2.1 Goal and Scope Definition

The goal of this study is to proposes a new method of energy performance evaluation to better understand the energy efficiency behaviour especially for exploring energy potential in machining systems. The functional unit that is considered is a typical machining system that could be a or several machine tools, machining production line. In terms of system boundary, the manufacturing cycle of one workpiece is, in principle, a cradle to grave exercise. However, in some cases cradle to gate, gate to gate, gate to cradle or, more recently, cradle to cradle approaches are possible. In the case of the machining system, the approach can only be

gate to gate as there can be many different applications later. Therefore, the whole gate to gate process within the system boundary includes machining for the workpiece from the raw material to the qualified workpiece in the mechanical manufacturing workshop.

2.2 Energy Performance Characteristics

It is not clear about what the energy efficiency and energy efficiency potential characteristic of the machining systems and how to quantify the energy performance. Understanding the energy consumption and energy saving potential rules of machining systems are conducive to improve the energy efficiency level and reduce energy consumption. For energy consumption and energy efficiency in machining, traditional methods are simply to monitor the actual energy consumption and to perform the comparison between the actual energy consumption and desired energy consumption. Therefore, traditional methods offer no substantial help for improving the energy management or increasing the energy-efficiency in the machining process.

Frist, to analyze the energy efficiency from the broad sense, based on previous studies, an energy performance curve of machining systems is described in Fig. 1. taking a machining product to be manufactured for example, some important concepts need to introduced including four kinds of energy, three kinds of energy systems and four kinds of system adaptability for the product.

The four kinds of energy for a machining product comprise real energy, benchmark energy, optimal energy, and energy saving potential. Real energy (RE) is the real energy consumption of a manufacturing product, a manufacturing process or an industrial system, and the value is the representations of the specific energy consumption in historical production. Benchmark energy (BE) is a value of the benchmarking for measuring the energy efficiency level,

and the value of the BE can be determined in terms of current methods including the calculation method, statistical analysis, etc. Optimal energy (OE). is a value of the perfect state under the special environment. Energy saving potential (ESP) is the amount with energy saving under the specific conditions.

Three kinds of energy systems comprise the low, medium and high energy efficiency system. The machining product has different specific energy consumption (SEC) in different industrial systems. Even so, the same system that is low, medium and high energy efficiency system may be various SEC due to differences in system adaptability for the machining product. For example, in the medium system, the SEC has obvious differences under the SA_1 and SA_2 due to the differences in system adaptability.

Four kinds of system adaptability (SA) for the machining product include SA_a, SA_c, SA_o and SA_l. The system adaptability is the superiority of the manufacturing equipment, process plans and parameters for product and operation behavior. If the better the SA, the larger the ESP is. The SA_a is the worst that the production system may be behindhand, and the industrial systems is not suitable to production and should be weeded out. The SA_c is a demarcation point that has a medium performance of industrial system with good manufacturing equipment, process plans and parameters for production. The SA_o is demarcation point that has an excellent performance of industrial system with advanced manufacturing equipment, process plans and parameters for production. Therefore, the SA_l is perfect state of the industrial system by various advanced technologies under the special environment.

From above analysis, improving the manufacturing equipment, process plans and parameters for production or operation behavior is an effective measure to reduce the SEC. It is well known that, in some cases, the current SEC of the machining can be reduced and its energy efficiency also can be further increased. Current almost few concept and method to describe the status. Due to the severe lack of a systematic theory for energy performance improvement so far, the study meets a bottleneck about how to measure energy efficiency and to explore their energy potential for machining. These seriously hinder the development to increase energy efficiency. To overcome these challenges, based on previous studies [38, 39], our research team proposed a novel approach to provide an effective tool to measure energy performance and explore energy potential.

Almost all industrial systems have different energy-saving potential levels. For example, the process manufacturing industries (i.e. steel and cement industry) can improve energy efficiency and reduce energy use through the advanced equipment and standard management, etc.; the discrete manufacturing industries (i.e. mechanical manufacturing industry) also can increase energy performance by
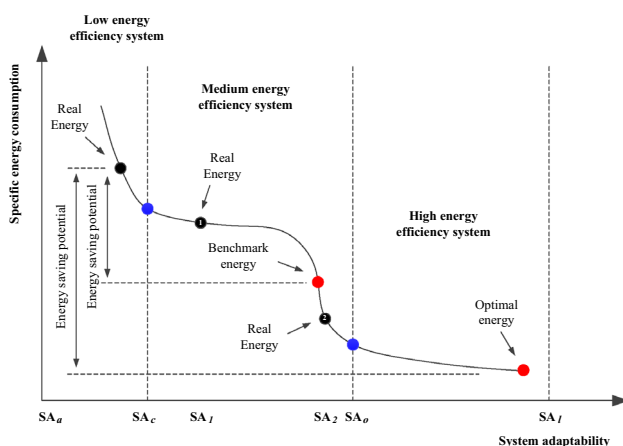

Fig. 1 Energy efficiency curve of the machining systems

advanced equipment and excellent parameters, etc. In the machining, whatever are a product, a production process or an industrial system, it is so difficult for reflecting energy potential level and latent energy conditions currently. Therefore, energy benchmark-based energy performance evaluation of machining is a basis of implementing energy conservation and emission reduction.

2.3 Benchmark-based Energy Performance Evaluation

2.3.1 Indicators of Energy Performance

To perform the energy performance evaluation of machinings using energy benchmarking, some indicators of energy performance could be described. Minable real energy (MRE) is the real amount with ESP under the specific conditions. The minable real energy can be expressed by MRE. The minable real energy is energy saving amount between real energy and benchmark as shown in Eq. (1). Moreover, for the minable real energy, there are the maximum minable real energy (MRE_{Max}) and minimum minable real energy (MRE_{Min}). The maximum minable real energy is the minimum real amount in machining process that also is amount of energy saving; on the contrary, and minimum minable real energy is the maximum real amount. Therefore, the bigger minable real energy is, the energy saving potential better (or current energy efficiency worse). The MRE_{Max} and MRE_{Min} are as shown in Eqs. (2) and (3).

$$MRE = RE - BE \tag{1}$$

$$MRE_{Max} = RE_{Min} - BE \tag{2}$$

$$MRE_{Min} = RE_{Max} - BE \tag{3}$$

How to measure the advantage of some machining method, it is necessary to introduce the MRE. In the machining, the value of the MRE is various, and the difference of minable real energy is larger due to the use of different energy mining methods (production methods). The degree of deviation between the real energy and benchmark energy represented by minable real energy also measures the energy efficiency level of the systems. For all value of minable real energy of the system, the maximum minable real energy and maximum minable real energy stand for the energy saving potential level under current production technology. Realistically, minable real energy relative value is a plus or minus sign. If the closer to MRE comes to the MRE_{Max}, the MRE is larger and this machining is energy-intensive with worse method but with greater energy saving potential; If the closer to MRE comes to the MRE_{Min}, the MRE is smaller and this machining is energy-efficiency with better

method but fewer energy saving potential. Meanwhile, the MRE_{Max} and MRE_{Min} are a plus or minus sign, but MRE_{Max} is the positive number in general; the MRE_{Min} is the positive number or negative number. Minable energy liveness is a quantitative range of minable real energy under current energy saving methods. The minable energy liveness (MEL) can be described.

$$MEL = \left| MRE_{Max} - MRE_{Min} \right| \tag{4}$$

or

$$MEL = \left| \left(RE_{Min} - BE \right) - \left(RE_{Max} - BE \right) \right| \tag{5}$$

According to Eq. (4), it can be found that minable energy liveness is a range value and is an absolute value. The range of minable energy liveness depends on the varieties and differences of methods for energy mining. If the smaller the varieties and differences of methods are, the range is smaller; If the larger the varieties and differences of methods are, the range is larger. The reason for the smaller range is because there are two situations: (i) the current methods for energy mining may be disadvantage with lack of technical improvement and advancement resulting in the unsatisfactory of energy saving; and (ii) the current methods for energy mining may be advantage with technical improvement and advancement, and the results of energy saving are satisfactory. For the reason for the larger range, results are similar. Therefore, although the minable energy liveness can stand for the energy saving potential, the specific representation with advancement of energy saving methods is difficult. The minable optimal energy and energy mining rating can be introduced to solve this problem.

Minable optimal energy is the optimal amount with energy saving potential under the specific conditions. The minable optimal energy can be expressed by MOE. The minable optimal energy is to describe the energy saving limit, and the minable optimal energy generally is the maximum minable energy limit without minimum minable energy limit. The minable optimal energy is as shown.

$$MOE = MRE_{optimal} = RE_{minimum\_optimal} - BE \tag{6}$$

The minable optimal energy is optimal amount be able to explore energy potential, and also is the maximum energy saving. The minable optimal energy is a generalized concept with various level characteristic of the plant level, regional level and national level. For the different levels of the machining, the minable optimal energy of an industrial system is different, even differences are larger due to differences of advanced equipment, standard management, excellent parameters, etc. Thus, to analyze the minable optimal energy of a system, the scope and boundary should be determined. On basis of the optimization and use of advanced

equipment, standard management, excellent parameters, the minable optimal energy can be acquired. Actually, the minable optimal energy is a virtual value or ideal value. If the closer to RE comes to the MOE, the current industrial system is more advanced; whereas, it is more outdated.

Energy saving efficiency is to describe the energy efficiency and energy saving potential of machining systems with some machining methods. The energy saving efficiency includes maximum minable energy efficiency (MEE_{Max}), minimum minable energy efficiency (MEE_{Min}), and minable energy efficiency (MEE). The three kinds of energy efficiency are as followed.

$$MEE_{Max} = \frac{MRE_{Max}}{MLE} \tag{7}$$

$$MEE_{Min} = \frac{MRE_{Min}}{MLE} \tag{8}$$

$$MEE = \frac{MRE}{MLE} \tag{9}$$

The maximum minable energy efficiency is the ratio of the maximum minable energy to the minable optimal energy, and is an index to describe the maximum minable efficiency of current production equipment with $MEE_{Max} \leq 1$. The minimum minable energy efficiency is the ratio of the minimum minable energy to the minable optimal energy, and is an index to describe the minimum minable efficiency of current production equipment with $0 \leq MEE_{Min} < 1$. The moment minable energy efficiency is the ratio of the moment minable energy to the minable optimal energy, and is an index to describe the moment minable efficiency of current production equipment with $MEE \leq 1$.

To use this energy indictors to analyze the energy saving potential of machining systems, a schematic diagram of energy analysis is proposed as shown in Fig. 2. Figure (a) and (b) represent the energy analysis map, the difference
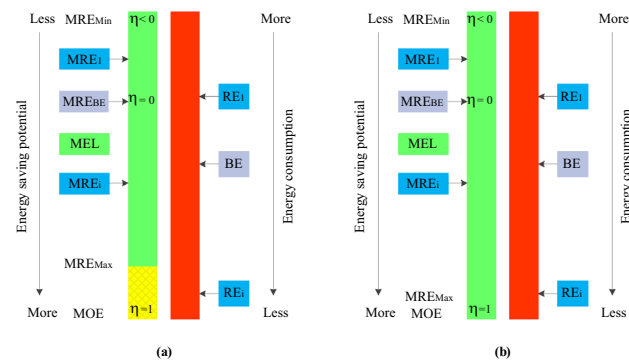
is only equal to MRE_{Max} and MOE. From the Fig. 1, this red line of the right represents the absolute values of the real energy and benchmark energy. RE_1 and RE_i are the real energy in the systems, and the energy consumption can be measured by prediction methods, statistical analysis and online acquisition. For the green line and yellow line of the left, they are relative values. The value of MRE_{BE} is 0, and energy saving of current machining is also 0 that its real energy use is same as the benchmark. The MRE_1 and MRE_i are the energy saving level of machining. The energy saving efficiency of the MRE_1 is less than zero showing that current machining is energy-efficiency production with high energy efficiency. The energy saving efficiency of the MRE_i is more than zero with energy-intensive production. Given that $\eta = 1$, the production has reached its optimal level of energy saving in current system level.

2.3.2 Energy Performance Evaluation Based on Energy Benchmark

To further perform the tool of energy analysis to measure energy efficiency and explore energy potential, therefore, the energy performance benchmark and processes can be developed on basis of above indictors. The object of energy analysis is the machining; however, the machining is the main body of energy consumption of product. Therefore, in this study, we develop the energy performance benchmark for product that helps to measure energy efficiency and explore energy potential of machining systems. The energy performance benchmark can be designed, and the operation procedures are summarized as shown in Fig. 3.

In the (b) of the Fig. 3, it is a very important measure benchmark, namely energy analysis instrument (EAI). The EAI can be designed to measure MEE reflecting the energy saving level and potential of machining systems. The range of the EAI is − 0.4 to 1.0 generally, it is hardly involved under the value (−0.4) of MEE. The background color is different and indicates that the MEE is more and more large, and the energy saving level and potential of
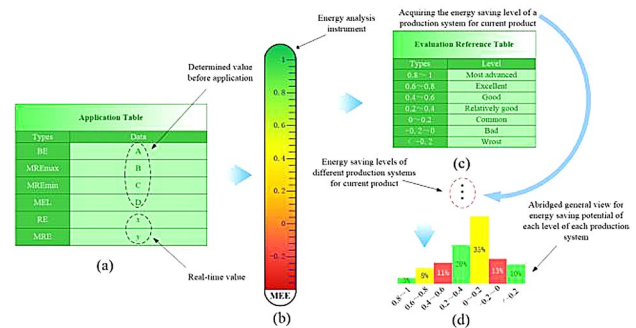

Fig. 2 Energy analysis map

Fig. 3 Energy performance benchmark and operation procedures

machining systems is better and better from the red to green of the background color of EMI.

The Fig. 3 shows that operation procedures of energy analysis comprise four steps: (i) establishing the application table, (ii) acquiring the MRE using the energy analysis instrument, (iii) determining the energy saving level by evaluation table, and (iv) analyzing energy saving potential of each machining for the product. For the first step (establishing the application table), the application table should be determined with important data including BE, MRE_{Max}, MRE_{Min} and MEL before measuring the MRE; in other words, the value of BE, MRE_{Max}, MRE_{Min} and MEL is certain for the same product. We only need collect or acquire the RE under the current machining, and the MRE also can be determined in terms of above theory. Then, the MRE can be graded using EAI. According to MRE, the energy saving level and potential is quantized for current machining and provides crucial technical support for energy efficiency improvement. Finally, if grasping the overall energy efficiency level of machining systems, the statistical analysis can offer help in the (d) of Fig. 3.

To apply the proposed method to measure energy performance and explore energy potential of machining systems, the machining system as a type machining can be studied. With a wide distribution and large amount of energy consumption at a low efficiency, machining systems have considerable energy-saving potential. For machining systems, this study not only illustrates the process to energy mining, but also analyzes the practicability of the energy analysis and energy saving potential of machining systems in a real production process.

The gear is regarded as a representative machining product in mechanical manufacturing industry and is an important symbol that measures the machining level. Therefore, this study is to establish energy mining benchmark to analyze the energy saving potential of a S148-1331 gear in the Chongqing Machine Tool Works Co., Ltd., China. Parameters of the gear include tooth member (36), modulus (2), pressure angle (20°), helix angle (20°) and full tooth depth (4.5 mm), and the gear and parameters are as shown in Fig. 4. Production of the gear comprises the blank making process, the gear blank making process, and the hobbing process, and a gear consists of three machine tools from the blank making process to qualified product. In this firm, the production process is various with different machine tools, i.e. CD6140A, GSK-980TDb, YB3120M, YE3120CNC7 and YKS3120, resulting the differences of energy use and energy efficiency. The energy consumption for 24 kinds of different machining plans is collected in Fig. 5. The number (No.1–No.24) in Fig. 5 is endowed with specific machining systems that comprise the machine tools and corresponding machining parameters.

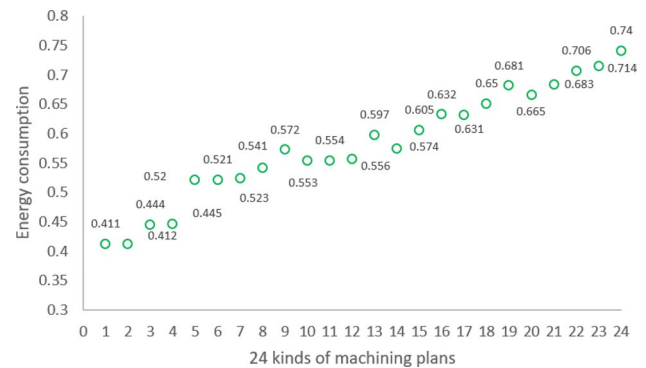**Fig. 4** S148-1331 gear and parameters

Fig. 5 Energy consumption of the gear for 24 kinds of different machining plans

3 Results and Discussion

Realistically, we had an in-depth study on the energy benchmark and acquired the value of energy benchmark that was 0.539kWh in the published paper [38]. Meanwhile, the RE_{Max} and RE_{Min} also can be determined and are 0.740kWh and 0.410kWh, respectively. Therefore, application table can be established in Table. 1.

According to real production of the gear, the whole of production involves 24 kinds of different machining process or machining plan constituted by different machine tools and machining parameters, even different spindle speed of machine tools. The machine tools involve the various types such as CD6140A, GSK980TDb, YB3120M, YE3120CNC7 and YKS3120. The machining parameters for each procedure is also different. Taking an example for one of machining plan, the specific detail information is in Table. 2.

Table 1 Application table of energy analysis for S148-1331 gear

Application table	
Types	Data
BE	0.539kWH
MRE_{Max}	0.201kWH
MRE_{Min}	0.128kWH
MLE	0.128kWH
RE	Independent variable
MRE	Dependent variable

The different machining processes or machining plans constitute different machining systems, thus, there are 24 machining systems for the gear. The RE under these machining processes are collected as shown in Table 3. Therefore, the MRE can be calculated using above model, and the schematic diagram of energy mining for these machining systems is as shown in Fig. 6. Figure 6 shows the energy efficiency level and energy saving potential of each machining system. The distribution of energy efficiency level is summarized in Table. 4.

The Table 4 shows that the energy efficiency level of twenty-four machining systems is different with lager differences, and the high energy efficiency level of machining systems is a few including two most advanced levels (i.e. 5th and 6th machining systems) and two excellent levels (i.e. 11th and 12th machining systems), respectively. The

Table 3 RE of the gear under different machining systems

No. of production system	RE (kWh)	No. of production system	RE (kWh)
1	0.523	13	0.632
2	0.541	14	0.650
3	0.572	15	0.680
4	0.597	16	0.706
5	0.411	17	0.520
6	0.411	18	0.520
7	0.556	19	0.665
8	0.574	20	0.683
9	0.605	21	0.714
10	0.631	22	0.740
11	0.444	23	0.553
12	0.445	24	0.554

good and relatively good energy efficiency levels of machining systems are very scarce. There are three machining systems with common energy efficiency. By contrast, there are a mass of machining systems that belongs to the bad and worst efficiency levels about seventeen machining systems. Meanwhile, analyzing energy efficiency level and energy saving potential in Fig. 7, it can be found that the high and common energy efficiency machining systems occupy merely 16.7% and 12.5% of the total machining systems, respectively. Especially for the low energy efficiency, they

Table 2 Main process parameters of a machining plan for the gear

Machine Tools	Content	Spindle speed (rpm)	Feed (mm/r)	Depth of cut (mm)
CD6140A	Turning (Φ90mm)	560	0.198	4.0
	Turning (Φ86mm)	560	0.198	1.4
	Drilling	220	–	–
	Turning (Φ44mm)	560	0.396	3.0
	Turning (Φ44mm)	560	0.396	3.0
	Turning (Φ44mm)	560	0.396	2.5
	End turning	560	–	2.3
GSK980TDb	Turning(Φ84.6 mm)	360	0.200	3.1
	Turning(Φ85.1 mm)	500	0.150	1.0
	End slot turning	100	0.020	8.7
	End slot turning	100	0.040	3.3
	End of turning	500	0.200	1.5
	Turning (Φ44mm)	500	0.120	1.0
	Turning (Φ43mm)	500	0.150	3.5
	Turning (Φ40.5 mm)	500	0.110	0.6
	Boring (Φ27mm)	500	0.150	1.0
	Boring (Φ28mm)	500	0.120	1.0
	End slot turning	130	0.030	8.7
	End slot turning	130	0.030	3.3
YB3120M	Hobbing	130	2.4	3.0
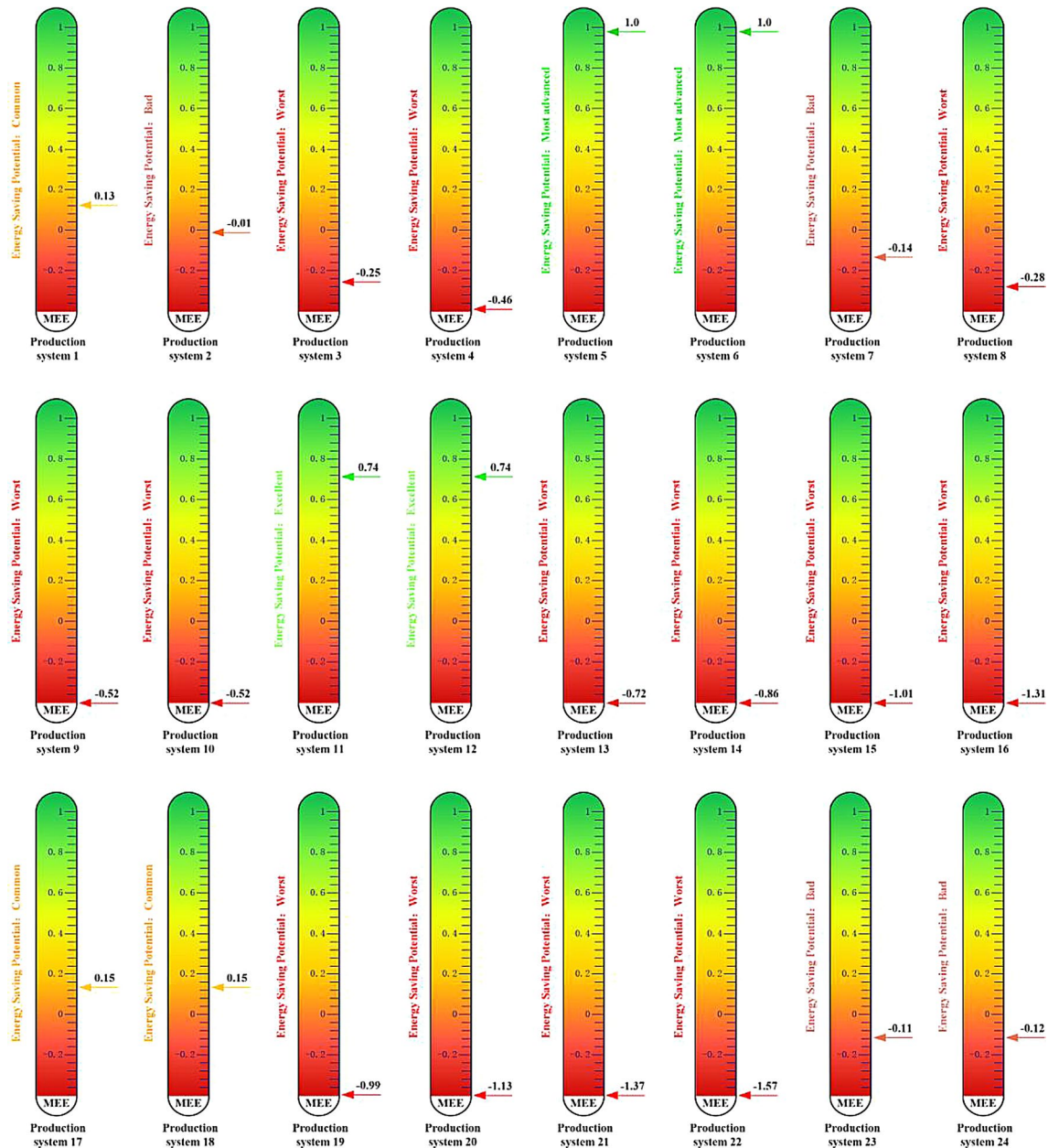
Fig. 6 The schematic diagram of energy analysis for these machining systems

occupy the 70.8% of machining systems showing that a mass of energy has been wasted, also another reflection of current low energy efficiency machining system possesses considerable energy saving potential by energy mining technology.

In terms of the measured energy efficiency of these machining systems, firms and energy management department can implement energy benchmark to energy-efficient production with being subjected to financial and administrative penalty in terms of the extent beyond the benchmark. If using advanced machining equipment (machine tools) like 5th and 6th machining systems and weeding

out backward machining equipment (machine tools) like 15th and 16th machining systems, there are energy saving potential for the 70.8% gears in machining systems by the energy mining, and decrease in energy was about 4.01kWh for unit gear with total energy efficiency improvement of 29.2%. Therefore, the proposed energy mining not only can measure the energy efficiency and explore energy potential, but also can strengthen energy monitoring and management and improving energy efficiency in the machining systems.

Table 4 Distribution of energy efficiency level for these machining systems

Energy efficiency level	Amount	Specific machining system
Most advanced	2	5th and 6th
Excellent	2	11th and 12th
Good	0	–
Relatively good	0	–
Common	3	1th, 17th and 18th
Bad	4	1th, 7th, 23th and 24th
Worst	13	3th, 4th, 8th, 9th, 10th, 13th, 14th, 15th, 16th, 19th,20th,21th and 22th
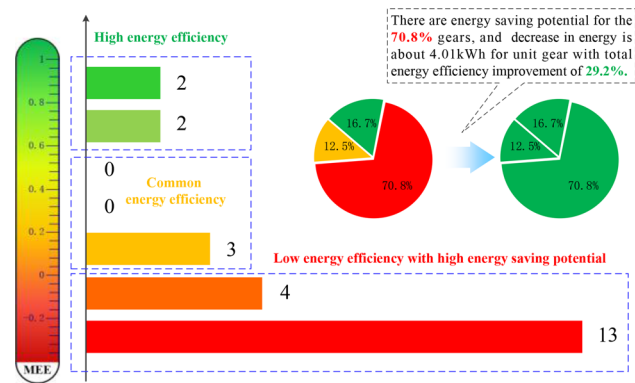
Fig. 7 Analysis of energy performance analysis

4 Conclusions

Current machining still lacked approaches and tools to better understand the energy efficiency behavior due to the severe lack of a systematic theory for energy efficiency improvement so far. The study met a bottleneck about how to measure energy efficiency and to explore their energy potential for machining systems. These seriously hindered the development to increase energy efficiency. Therefore, this study addressed energy benchmark-based energy performance evaluation of machining. The results of the study were summarized as follows:

Firstly, analysis on energy performance of machining is introduced including benchmark energy, optimal energy, energy efficiency system, system adaptability. This paper proposed some energy performance indicators to analyze the energy performance of machining systems including the benchmark energy, minable real energy, minable potential liveness, minable optimal energy, energy saving efficiency. Secondly, to further perform the tool of energy analysis to measure energy performance and explore energy potential, therefore, the energy performance benchmark and processes are introduced: (i) establishing the application table, (ii) acquiring the MRE using the energy analysis instrument, (iii) determining the energy saving level by evaluation table, and (iv) analyzing energy performance of each machining for the product. Finally, to apply the proposed method and to evaluate energy performance of machining systems, the machining system as a type machining can be studied. The energy performance evaluation based on energy benchmark was applied to a mechanical manufacturing industry in China, showing that the proposed method was feasible for establishing an energy potential diagram and performing energy potential analysis for gears in machining systems and can play a crucial role in improving energy management and promoting energy saving and emission reduction.

Future studies will comprise two aspects. First, the energy evaluation standard and certification of machining systems will be considered using the energy performance evaluation method. Second, data acquisition for establishing more fundamental energy databases will be implemented continuously.

References

1. Cai, W., Li, L., Jia, S., et al. (2020). Task-oriented energy benchmark of machining systems for energy-efficient production[J]. *International Journal of Precision Engineering and Manufacturing-Green Technology, 7*(1), 205–218.
2. Chen, G. Q., Wu, X. D., Guo, J., et al. (2019). Global overview for energy use of the world economy: Household-consumption-based accounting based on the world input-output database (WIOD). *Energy Economics, 81*, 835.
3. Duflou, J., Sutherland, J., Dornfeld, D., et al. (2012). Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Annals -Manufacturing Technology, 61*(2), 687–609.
4. IEA (International Energy Agency), Energy efficiency (2017). IEA World Energy Statistics and Balances (database), OECD/IEA, Paris, www.iea.org/statistics/relateddatabases/worldenergystatisticsandbalances/
5. IEA (2017c), Mobility Model (database), (2017). OECD/IEA, Paris, www.iea.org/etp/etpmodel/transport/ (accessed 25 May 2017).
6. IEA (2017d), Energy Technology Perspectives, (2017). (Residential Model), OECD/IEA, Paris, www.iea.org/etp/.
7. Ke, J., Price, L., McNeil, M., et al. (2013). Analysis and practices of energy benchmarking for industry from the perspective of systems engineering. *Energy, 54*, 32–44.
8. Hu, L., Cai, W., Shu, L., et al. (2021). Energy optimisation for end face turning with variable material removal rate considering the spindle speed changes. *International Journal of Precision Engineering and Manufacturing-Green Technology, 8*(2), 625–638.

9. Liang, C., Feng, H., & Chun, L. (2014). Energy efficiency benchmarking of energy-intensive industries in Taiwan. *Energy Conversion and Management, 77*, 216–220.

10. S, Turetskyy A, Loellhoeffel T, , et al. (2020). Machine learning approach for systematic analysis of energy efficiency potentials in manufacturing processes: A case of battery production. *CIRP Annals -Manufacturing Technology, 69*(1), 21–24.

11. ISO 14955–1:2014. (2014). Machine tools e environmental evaluation of machine tools -part 1: design methodology for energy-efficient machine tools. International Organization for Standardization (ISO).

12. European Union. Directive 2012/27/EU of the european parliament and of the council of 25 October 2012 on energy efficiency, amending directives 2009/ 125/EC and 2010/30/EU and repealing directives 2004/8/EC and 2006/32/EC.2012 [accessed: 12.05.2015] Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri¼OJ:L:2012:315:0001:0056:EN:PDF

13. JIS TS B 0024–1:2010. (2010). Machine tools – test methods for electric power consumption – part 1: machining centres. Japanese Standards Association

14. Industrial Assessment Centers (IAC). Energy Efficiency & Renewable Energy of U.S. DOE [EB/OL] <http://iac.rutgers.edu/about.php>; 2012–06–04

15. European Commission. EUROPE (2020). a strategy for smart, sustainable and inclusive growth; 2010. http://ec.europa.eu/europe2020/index_en.htm

16. National technical committee on energy fundamentals and management of standardization administration of China. (2013). *GB/T12723-2008 General principles for establishing allowance of energy consumption per unit throughput*. Beijing: Standards Press of China.

17. Roedger, B. J., Schoenemann, M., et al. (2020). Combining life cycle assessment and manufacturing system simulation: evaluating dynamic impacts from renewable energy supply on product-specific environmental footprints. *International Journal of Precision Engineering and Manufacturing-Green Technology*. https://doi.org/10.1007/s40684-020-00229-z

18. Shi, X. (2014). Setting effective mandatory energy efficiency standards and labelling regulations: A review of best ractices in the Asia Pacific region. *Applied Energy, 133*, 135–143.

19. Guo, Y., Duflou, J., Deng, Y., et al. (2018). A life cycle energy analysis integrated process planning approach to foster the sustainability of discrete part manufacturing. *Energy, 153*, 604–617.

20. Reddy, B. S. (2013). Barriers and drivers to energy efficiency–A new taxonomical approach. *Energy Conversion and Management, 74*, 403–416.

21. IPCC (Intergovernmental Panel on Climate Change). Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Chapter 5. Barriers, Opportunities, and Market Potential of Technologies and Practices. Retrieved on October 30, 2008 fromhttp://www.grida.no/publications/other/ipcc_tar/?src=/climate/ipcc_tar/wg3/index.htm

22. Leiden, A., Herrmann, C., & Thiede, S. (2020). Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. *Journal of Cleaner Production, 280*, 125160.

23. Kara, S., & Li, W. (2011). Unit process energy consumption models for material removal processes. *CIRP Annals Manufacturing Technology, 60*(1), 37–40.

24. Bunse, K., Vodicka, M., Schönsleben, P., et al. (2011). Integrating energy efficiency performance in production management–gap analysis between industrial needs and scientific literature. *Journal of Cleaner Production, 19*(6), 667–679.

25. de Groot, H., Verhoef, E., & Nijkamp, P. (2001). Energy saving by firms: Decision-making, barriers and policies. *Energy Economics, 23*(6), 717–740.

26. Worrell, E., Bernstein, L., Roy, J., et al. (2009). Industrial energy efficiency and climate change mitigation. *Energy efficiency, 2*(2), 109.

27. Lo, K. (2014). A critical review of China's rapidly developing renewable energy and energy efficiency policies. *Renewable and Sustainable Energy Reviews, 29*, 508–516.

28. Wang, Q., Zhao, Z., Zhou, P., et al. (2013). Energy efficiency and production technology heterogeneity in China: A meta-frontier DEA approach. *Economic Modelling, 35*, 283–289.

29. Lin, B., & Du, K. (2013). Technology gap and China's regional energy efficiency: A parametric metafrontier approach. *Energy Economics, 40*, 529–536.

30. Lin, B., & Du, K. (2014). Measuring energy efficiency under heterogeneous technologies using a latent class stochastic frontier approach: An application to Chinese energy economy. *Energy, 76*, 884–890.

31. Taylan, O., Kaya, D., & Demirbas, A. (2016). An integrated multi attribute decision model for energy efficiency processes in petrochemical industry applying fuzzy set theory. *Energy Conversion and Management, 117*, 501–512.

32. Zhu, Q., Lujia, F., Mayyas, A., et al. (2015). Production energy optimization using low dynamic programming, a decision support tool for sustainable manufacturing. *Journal of Cleaner Production, 105*, 178–183.

33. May, G., Barletta, I., Stahl, B., et al. (2015). Energy management in production: A novel method to develop key performance indicators for improving energy efficiency. *Applied Energy, 149*, 46–61.

34. US EPA. ENERGY STAR – the power to protect the environment through energy efficiency. US Environmental Protection Agency; Washington, DC; 2003

35. Dietmair, A., Verl, A., & Eberspaecher, P. (2011). Model based energy consumption optimisation in manufacturing system and machine control. *International Journal of Manufacturing Research, 6*(4), 380–401.

36. Boyd, G., Dutrow, E., & Tunnessen, W. (2008). The evolution of the '"energy star"' energy performance indicator for benchmarking industrial plant manufacturing energy use. *Journal of Cleaner Production, 16*(6), 709–715.

37. Zhou, X., Liu, F., & Cai, W. (2016). An energy-consumption model for establishing energy-consumption allowance of a workpiece in a machining system. *Journal of Cleaner Production, 135*, 1580–1590.

38. Cai, W., Liu, F., Xie, J., et al. (2017). A tool for assessing the energy demand and efficiency of machining systems: Energy benchmarking. *Energy, 138*, 332–347.

39. Cai, W., Liu, F., Zhang, H., et al. (2017). Development of dynamic energy benchmark for mass production in machining systems for energy management and energy-efficiency improvement. *Applied Energy, 202*, 715–725.

40. Park, C. W., Kwon, K. S., Kim, W. B., et al. (2009). Energy consumption reduction technology in manufacturing—A selective review of policies, standards, and research. *International Journal of Precision Engineering and Manufacturing, 10*(5), 151–173.
41. Wang, Q., Liu, F., & Li, C. (2013). An integrated method for assessing the energy efficiency of machining workshop. *Journal of Cleaner Production, 52*, 122–133.
42. Gao, M., Li, L., Wang, Q., et al. (2020). Energy efficiency and dynamic analysis of a novel hydraulic system with double actuator. *International Journal of Precision Engineering and Manufacturing-Green Technology, 1*, 1–13.
43. Yoon, H. S., Kim, E. S., Kim, M. S., et al. (2015). Towards greener machine tools–A review on energy saving strategies and technologies. *Renewable and Sustainable Energy Reviews, 48*, 870–891.

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