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A Low-Cost Monitoring System for Energy Consumption Analysis During Machining Operation

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Abstract

CNC machining is a common manufacturing process which requires significant energy consumption. The first step towards energy savings is to monitor the energy consumption of CNC machines, which are usually equipped with a three-phase electrical power supply. However, existing energy metres are costly for detailed measurements of a machine's energy consumption level. This study developed a low-cost energy measurement device based on the Arduino microcontroller-based platform to monitor energy consumption during CNC machining processes. The product development methodology includes the measurement procedure, calibration, pilot study prior to the commencement of the actual study, and results validation. A field experiment was conducted to validate the design's functionality. Preliminary energy measurements were performed on tool standby, tool changing, spindle rotation speeds, and feed rates. Results showed that the average standby power of the CNC machine is 5.15 kWh, with actual power consumption for the coolant pump motor, spindle motor, and feed motor being 0.43 kW, 0.77 kW, and 0.45 kW, respectively. Energy consumption is increased with spindle rotation speed and feed rate increments. The analysis results demonstrated the product's ability as a cost-effective solution for machining energy monitoring.

1. Introduction

Manufacturing is a very energy-intensive industry that accounts for a significant proportion of global energy consumption [1]. For high-volume production, computer numerical control (CNC) machining is a commonly employed manufacturing equipment due to its high degree of automation. The energy consumed during machining activities is a significant contributor to the overall energy consumption in the industry. To identify potential energy-saving possibilities and to improve the overall efficiency of the manufacturing process, it is essential to monitor and assess energy use throughout machining operations. Monitoring energy consumption is the essential towards identifying opportunities for energy usage and waste reduction. It is a data-driven approach for optimising energy usage in the long term.

The first step in reducing energy use is to keep an eye on how much energy a CNC machine consumes [2], which typically uses a three-phase electrical power supply. However, the challenge is that the level of a machine's energy consumption cannot be accurately and efficiently measured by conventional energy supply metres. Previously, a number of studies had been done on monitoring systems for analysing energy usage during CNC machining operations. In terms of instrumentation, power clamp metres or power metre with clip-on current transformer are the most common approach being used [3; 4]. Despite its simplicity that gives direct reading of voltage and current, it usually does not come with data logging capabilities and require manual recording. Pertaining to this, some researchers utilized a more sophisticated, industrial-grade power analyser (e.g., Fluke 435-II Power Quality and Energy Analyser) [5; 6]. Such an analyser enables easier sampling of power and energy consumption, with added features for fault analysis and troubleshooting. Although this type of device is useful for monitoring a single machine, it is expensive and not cost-effective when multiple machines need to be monitored simultaneously. In addition, these are non-permanent installation used to monitor energy consumption that requires manual transfer of energy data to a computer for further analysis.

Apart from using readily available energy metres, there are also researchers who has used customised energy monitoring setup. For instance, Chen et al. [7] proposes an IoT-based energy monitoring and workshop management system, which consists of industrial-grade sensors for power sensing. The sensors need to work alongside a custom-built software system to form an integrated solution for their purpose. Some other researchers used specialised monitoring equipment for energy sensing [8], which is complicated to setup and unsuitable in actual production settings. In the aforementioned cases, these are not very affordable to small and medium-sized enterprises (SMEs), especially when the energy consumption of more than one machine needs to be monitored constantly. In recent years, with the rise of readily available Internet of Things (IoT) devices, there has been a rising interest to develop customisable and affordable energy monitoring system for various practical applications, such as for monitoring building energy [9], agriculture farming energy [10], etc. These studies have shown the advantages of using off-the-shelf IoT devices as components of a customised energy monitoring system. Besides, the implementation of an open platform (e.g., Arduino) also offers flexibility and enables customisation to enhance the capabilities of the system, such as the possibility to add-on Lorawan gateway or mesh network for enhanced communication. The comparatively cheaper cost of such a system also provides the opportunity for improved scalability and facilitates widespread implementation.

This research paper describes the design and development of a low-cost monitoring system for energy usage analysis during machining operations. The system is based on the Arduino microcontroller-based platform and uses off-the-shelf sensor devices to measure various machining energies during processes such as spindle rotation, tool changing, and cutting forces. The suggested monitoring system offers several advantages: (1) it is inexpensive and simple to use, making it affordable to SMEs, research or training institutions who might lack the funding for deploying energy monitoring systems across multiple pieces of manufacturing equipment, (2) it uses commonly available components, which enables easier long-term system maintenance, (3) Compared to clamp meters, it allows for a permanent in-situ installation, with the ability to provide real-time capture of energy usage during machining operations at scale, which is useful for streamlining and optimizing the overall manufacturing operations, and (4) The open platform allows flexible configuration to extend the capabilities of the system. The following parts will provide a more comprehensive explanation of the design, development, and efficacy testing of this system.

2. Methodology

The objective of this study is to create, using the readily available microcontroller platform or single-board computer (SBC), and other readily obtainable sensing components on the market, a low-cost monitoring system for energy consumption analysis during CNC machining processes. Figure 1 shows the overall research framework for this study. As shown in the figure, this study consists of two main parts: the design part and the experimental part. Firstly, the design methodology applied in this study is an adaptation of the Engineering Design Process (EDP) thinking process [11]. Based on design thinking, EDP is an effective and adaptable method for solving engineering problems that can be used in a variety of contexts and includes phases such as empathise, define and ideate, prototype, test, and refine. The detailed explanation of each phase will be covered in the subsequent subsections that follow. The outcome of the design part is a working prototype of an energy monitoring system. The next part after this will be the field experimental part, where the system is deployed in an actual CNC machine and experiments of base energy consumption and energy consumption under multiple machining conditions (such as multiple spindle speeds and feed rates) are conducted. The results will be analysed in terms of the actual power and energy consumed during the process.

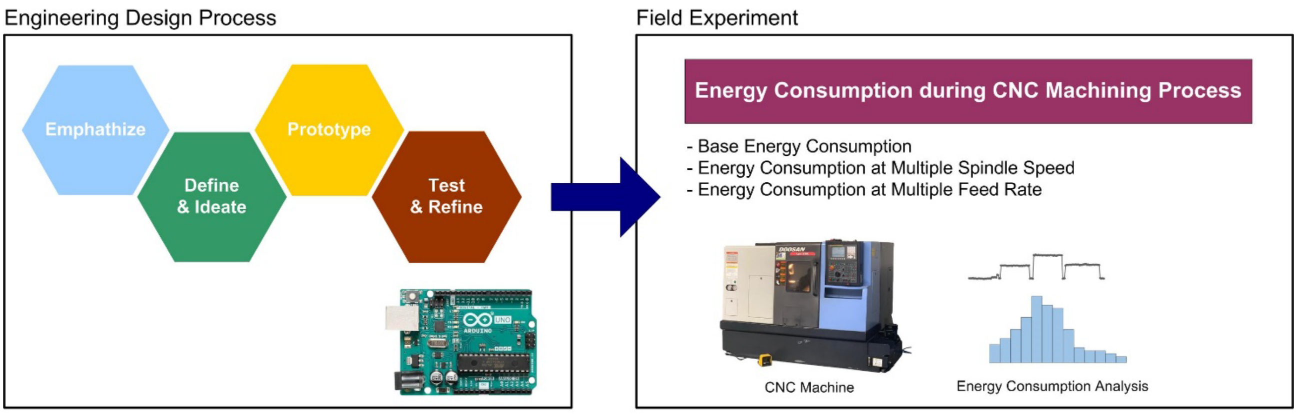

Fig. 1 *Research framework*

2.1 Phase 1: Emphathize

The empathize phase of the Engineering Design Process (EDP) involves understanding the needs of stakeholders who will be using the low-cost monitoring system for energy usage analysis during CNC machining processes. For this study, the developed monitoring system is to be installed and tested on a CNC lathe machine at a machining laboratory. In order to gain a better understanding of stakeholder needs and challenges, a simple interview has been conducted with the operator of the machine at the laboratory. A field survey and observation have also been conducted in relation to energy monitoring at the machining laboratory. Firstly, power specifications for the CNC lathe machine are obtained, and the power supply is determined to be a three-phased power supply. In addition, the findings of this phase have also revealed some issues related to energy consumption during CNC machining processes, such as rising electricity costs, difficulties in monitoring the energy usage of specific machines, and challenges in optimising energy consumption due to limited energy data availability. Based on the feedback, we reckoned that a low-cost monitoring system based on a single board computer (SBC) is feasible and can function as a cost-effective solution for monitoring and optimising energy consumption during CNC machining processes.

2.2 Phase 2: Define and Ideate

The first step in Phase 2 is to develop a detailed product specification. This stage describes the product's technical requirements, such as specifications, materials needed, and development procedures. To make sure the product can meet actual requirements, a few steps must be taken. Firstly, a preliminary power measurement is performed on the CNC machine during the basic machining process to estimate the actual voltage and current values. The purpose of this step is to decide which kind of sensor is suitable for the purpose of actual energy monitoring and, subsequently, the corresponding circuit design. Measurements were conducted at three conditions of the CNC machine: during start-up, during spindle rotation, and also during an actual machining operation. The results of this preliminary measurement stage are summarised in Table 1. The voltage values in Table 1 are root-mean-squared (rms) values, and all measurement data were obtained by a minimum of three repetitions and then averaged.

Table 1 *Summary of results from preliminary power measurement*

	Machine Condition	Voltage (RMS) (V)	Averaged Line Current (A)		
			Phase 1	Phase 2	Phase 3
1	Startup (Standby Power)	433.2	2.03	1.94	2.00
2	Spindle Rotation (2200 RPM)	432.9	4.58	3.95	4.02
3	Actual Machining Operation	433.7	5.02	4.95	5.10

From Table 1, it was found that voltage is generally stable at around 433.2 volts, and it also shows that the voltage readings are not affected by the current changes at each stage. In terms of current values, different values were observed under different machine conditions, and the changes can be significantly recorded. The averaged current values for each phase in general do not exceed 10A as per observation. Another important finding from this stage is that the current values are not the same for each line or individual phase, indicating that the three-phase power loading is imbalanced. For imbalanced loading, the following equation can be used for the calculation of total power consumption [12]:

$$P_T = V_P \left[I_A + I_B + I_C \right] \quad (1)$$

where P_T represents the total power consumption, V_p is the phase voltage, and I_A, I_B, and I_C represents the line current for each individual phase. All of these discoveries provide valuable information for the system's design considerations. A few design considerations for the monitoring system are as follows:

- **Programmable microcontroller:** This can be chosen in the form of a microcontroller board or single-board computer (SBC). The available choices on the market are Arduino, Raspberry Pi, and ESP32. Each of these microcontroller systems has its own advantages that can be suited for different applications. In this study, an Arduino-based microcontroller board is selected due to its simplicity, low power consumption, ease of programming, relatively mature codebase, and available online reference coding for further customisation.
- **Sensor devices:** Two parameters mainly need to be measured: voltage and current. For voltage, since its value is relatively stable, this parameter shall be measured and verified separately using industrial-grade clamp metres. The inclusion of this parameter in the monitoring system is complicated as it will involve a stepdown voltage transformer or converter (from 433 volts) with a corresponding stepdown circuit design to return a voltage reading that is safe and suitable to be recorded by the microcontroller system. All these translate to additional costs for the project. Furthermore, the majority of comparable Arduino projects seen online likewise assume that voltage measurements remain constant. As for the current sensor, the suitable current sensor chosen will be the SCT-013 sensor, which is capable of measuring up to 100A. This shall be sufficient to safely measure the current values as per the observation.
- **Data logging:** There are various ways that sensor data can be collected. One of the ways is to channel all collected sensor data through an online data aggregation, visualisation, and analysis platform. (such as ThingSpeak[1]), or the conventional way of logging all data through an SD memory card. During the initial site evaluation, it was discovered that the laboratory has poor connectivity owing to the lack of cellular phone signal and WiFi routers, resulting in the unavailability of internet access in the workshop setting. Thus, the memory card approach is chosen to capture the energy data in real-time.
- **Circuit design:** In this study, Proteus 8 Professional is used as the software for schematic circuit diagramming. Figure 2 shows the overall design of the circuit, which consists of the Arduino controller board, an SD card slot for data collection and storage, an LCD panel to showcase in real-time the power consumption information during experimentation, and three current sensor inputs. For each current sensor input, the corresponding circuit design is as shown in Figure 3. Figure 3 indicates the design of the current sensor input, which is each controlled by two resistors of 10 kΩ and 1 kΩ, and a 100 μF capacitor to smooth the current input.

[1] https://thingspeak.com

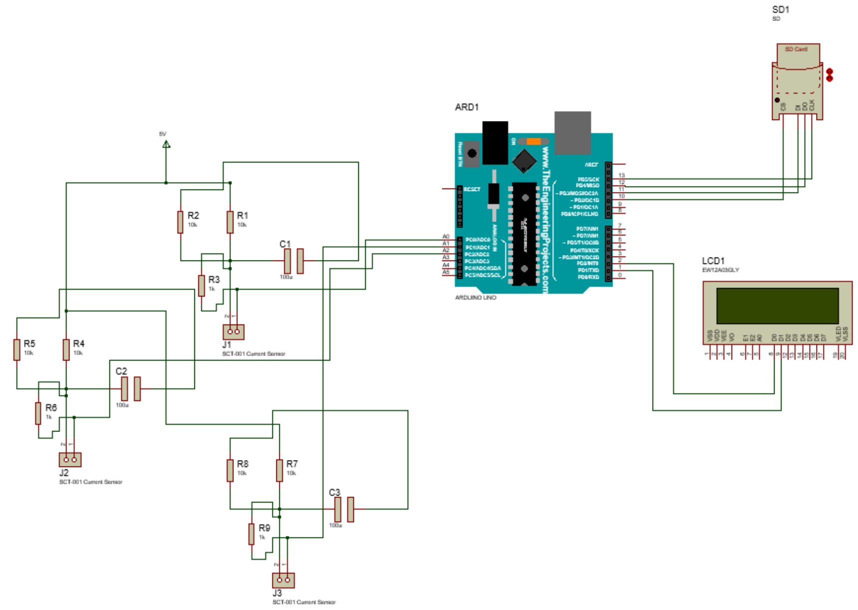

Fig. 2 *Schematic circuit diagram for the proposed energy monitoring system*

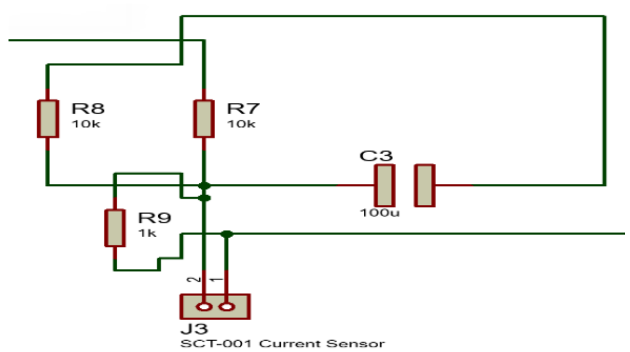

Fig. 3 *Circuit design for current sensor input*

2.3 Phase 3: Prototype

Based on the proposed system design, the next step in the methodology is to fabricate a system prototype, which includes developing the hardware system (i.e., circuits) and the corresponding software coding to ensure the project's functionality. The hardware system development includes ensuring the appropriate soldering of circuit connections and verifying that the resulting prototype can accurately measure energy measurements. This part also includes the circuitry embodiment design that makes it easier to be installed on the CNC machine. On the coding part, the corresponding coding for the programmable microcontroller is developed. This part mainly includes the frequency of energy data collection and the method for data collection and storage. Figure 4 shows the system prototype and coding work in progress. The completed prototype encapsulated in a circuitry embodiment is shown in Figure 5.

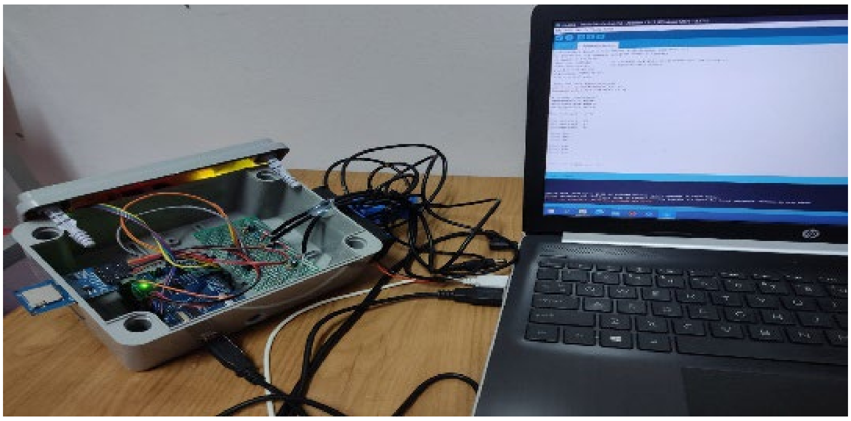

Fig. 4 *System prototype and coding during development*

Fig. 5 *Completed product with embodiment*

2.4 Phase 4: Test and Refine

This phase involves both testing and refining the prototype before it can be deployed for actual application. The purpose of testing is to ensure the full functionality of the prototype. At this stage, the prototype is installed on an actual CNC machine to test its functionality. The installation involves clipping the three current sensors at each phase of the three-phased power contact of the CNC machine. For voltage reading, an industrial-grade clamp metre with basic data logging capability is attached to the main power input to log the root-mean-squared (rms) averaged voltage over a period of measurement.

Fig. 6 *Setup for sensor calibration*

Upon installation, the next important step is to perform calibrated refinements in terms of energy reading accuracy. This involves the comparison of sensor readings with actual readings by a clamp meter. For this purpose, three clamp metres are clamped at the wire of each phase input. Figure 6 shows the overall setup for the current sensor calibration. After the CNC machine is switched on, readings on the LCD screen of the prototype and the clamp metre are observed. Any differences in readings are resolved by performing some code changes to alter the current printout on the LCD and also recorded sensor data. The result is accurate sensor readings that are the same as the actual current reading, as shown in Figure 7. Subsequently, additional surveillance is carried out to assess the sensors' ability to accurately capture readings in different machining conditions, such as varying spindle rotation speeds and feed rates. The aim is to determine if the obtained readings align with the measured values of the clamp metres.

Fig. 7 *Completion of sensor calibration after code changes*

3. Field Experiment

Upon the completion of the system development, the energy monitoring system is installed at a CNC lathe machine to verify its capability in estimating actual energy consumption. The energy consumption of a CNC machine can be decomposed into the required energy of the major components of the machine, for instance, the spindle, axis feed, coolant pump, tool change system, and other components that consume a fix amount of energy (e.g., the controller system). The total energy consumption for a CNC machine can be estimated as a sum of energy consumption for each component as follows [13]:

$$E_{total} = E_{fix} + E_{tool} + E_{cool} + E_{spindle} + E_{feed} \quad (2)$$

where E_{total} represents the total energy consumption of CNC machine during a machining operation. E_{fix}, E_{tool}, E_{cool}, $E_{spindle}$, and E_{feed} are the energy consumption of fixed energy, tool change system, coolant pump, spindle rotation, and axis feed, respectively. In order to determine each of the aforementioned energy components, energy consumption measurements need to be performed at each machining condition, which need to be activated using specific numerical control (NC) codes. The detailed experimental setup information for this purpose with the corresponding NC codes is summarised in Table 2.

Table 2 *Detailed experimental setup for energy consumption estimation with NC Codes*

Experiment No.	Measured Energy Component	NC Code	Behaviour Explanation
1	Fixed energy (Standby) (E_{fix})	G21;	CNC Machine switched ON
2	Machine tool change (E_{tool})	G0 M06 T08; M06 T0101;	Machine perform tool change from tool no. 1 at turret to tool no.8 and back to tool no.1.
3	Coolant pump motor (E_{cool})	M08; M09;	Coolant activated Coolant deactivated
4	Spindle motor ($E_{spindle}$)	G97 S1200 M03;	Spindle motor activated at 1200 RPM
5	Feed motor (x-axis and z-axis) (E_{feed})	G97 S900 M03; G0 G54 X0. Z0.; G1 Z-150 F0.2; G54 X0. Z0.;	Rapid traverse to origin position. Then moving to designated position of z-150 at the feedrate of 0.2mm/min. Then back to origin position.

The following are the detailed experimental procedures for performing the experiment at a CNC lathe machine:

1. Install the developed energy monitoring system on the CNC machine.
2. Switch on the machine and return the turret position of the machine to its origin position (x-0, z-0).
3. Switch on the energy monitoring system to ensure energy readings are available.
4. Using the manual data input (MDI) function of the CNC machine, manually input the NC codes as listed in experiment no. 1 of Table 1 into the machine and activate the code by pressing the *cycle start* button.
5. Energy readings are logged for a duration of at least one minute. After that, the operation is terminated by manually entering the NC code M05.
6. Repeat step 4 for the rest of the experiments as listed in Table 1 towards completion.

The obtained energy consumption data is presented graphically in terms of power consumption. Figure 8 shows the measured power consumption in kilowatts (kW) against time in seconds, with periods labelled in accordance with the multiple experiments listed in Table 2. Energy consumption for a duration of time is equivalent to the area under the power-time graph, and this can be feasibly determined using the trapezoid rule [14], which is defined as follows:

$$Energy\ (kWh)\ = (t_2 - t_1)/3600 \times (P_2 - P_1)/2 \quad (3)$$

where t and P represent the time (in seconds) and power (in kW), respectively. This is applied for each time interval. For instance, in order to determine the energy consumption in a minute with a 2-second interval, the energy consumption for every interval is calculated using the trapezoid rule equation, and then summed up to form the total energy consumption for a minute. Table 3 shows a summary of energy consumption results for each experiment as listed in Table 2. As witnessed in Figure 8, the power consumption during a period (i.e., from the indicated start time to the indicated end time) is quite stable with the averaged power value as indicated in Table 3. However, actual consumption needs to be calculated using the trapezoid rule. For instance, energy consumption for experiment 1 (standby energy) is calculated by summarising the energy consumption from t = 0s to t = 58s, which gives the results of 0.0829 kWh. Based on this averaged power consumption, we are able to determine the power consumption for all other CNC machine components. For example, in experiment 3 involving coolant operation, the measured power consumption is 5.58 kW, which indicates that coolant pump motor consumes 0.43 kW after deducting standby or idle energy. Using the same method, we can also determine

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that the spindle motor consumes 0.77 kW of energy at 1200 RPM (experiment 4), and the feed motor (at 0.2 mm/min) consumes 0.45kW (experiment 5). Overall, total energy consumption for the whole process (from experiment 1 to experiment 5) is 0.4421 kWh.

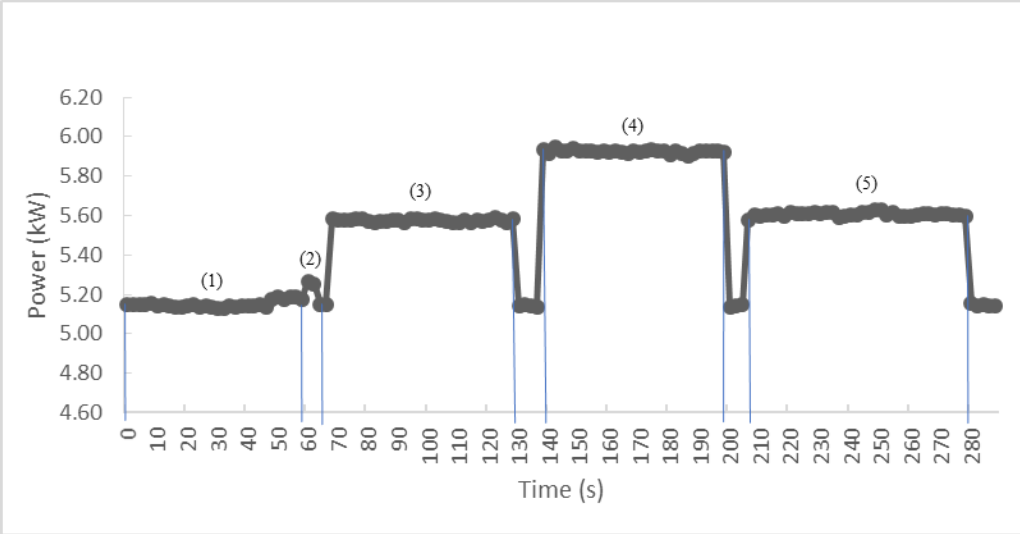

Fig. 8 *Power consumption during machining operation at different experimental stages (in Table 2)*

Table 3 *Summary of energy consumption under different experiment*

Experiment No.	Start Time (seconds)	End Time (seconds)	Average Power Consumption (kW)	Actual Energy Consumption (kWh)	Averaged Energy Consumption (kWh per minute)
1	0	58	5.15	0.0829	0.0858
2	58	64	5.25	0.0087	0.0870
3	68	128	5.58	0.0957	0.0957
4	138	198	5.92	0.1014	0.1014
5	206	278	5.60	0.1149	0.0958

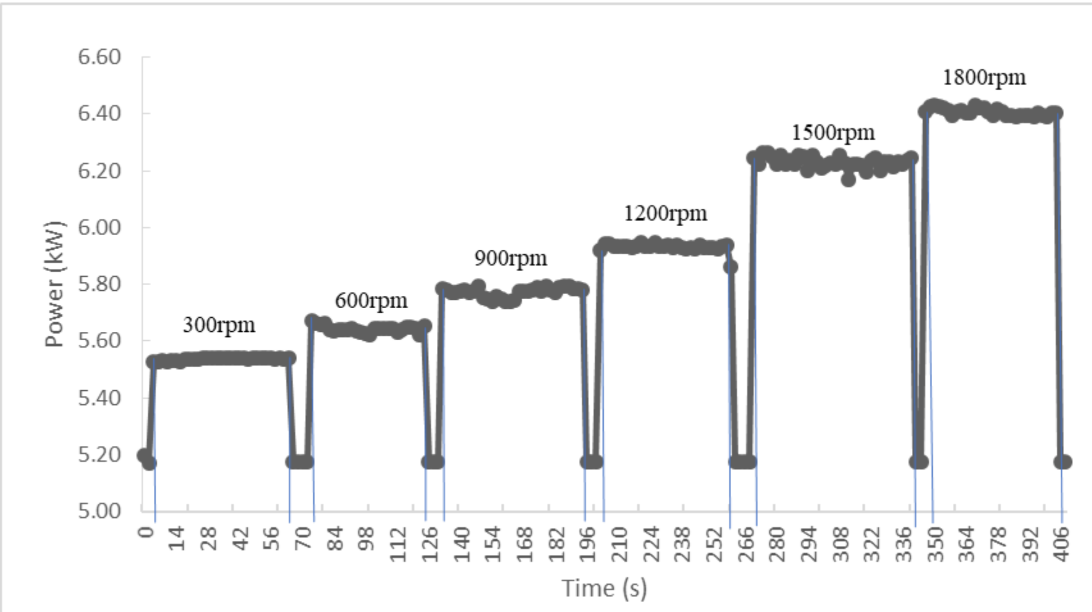

Fig. 9 *Power consumption at multiple spindle rotation speed*

Table 4 *Summary of energy consumption under multiple spindle rotation speed*

Spindle Rotation Speed (RPM)	Start Time (seconds)	End Time (seconds)	Average Power Consumption (kW)	Actual Energy Consumption (kWh)	Averaged Energy Consumption (kWh per minute)
300	4	64	5.54	0.0953	0.0953
600	74	124	5.62	0.0814	0.0977
900	132	194	5.76	0.1024	0.0991
1200	202	258	5.93	0.0954	0.1022
1500	270	340	6.25	0.1243	0.1065
1800	346	404	6.41	0.1064	0.1101

Subsequently, the experiment proceeds by measuring energy consumption in two typical machining scenarios: varying spindle rotation speeds and feed rates. This is done to examine the alterations in energy consumption. The energy readings obtained are then verified against the industrial-grade clamp metres. Figure 9 shows the power consumption under different settings of spindle rotation speed, with detailed experimental results as summarised in Table 4. From the figure, the power consumption pattern is quite stable for lower rotation speeds, with a little fluctuation at higher rotation speeds (1500 RPM and 1800 RPM). The averaged power consumption is as indicated in Table 4, and the actual energy consumption is calculated using the trapezoid rule. As the time duration for each RPM setting is different, and for the purpose of comparison across different rotation speeds, the averaged energy consumption per minute (kWh/minute) is derived. From the results in Table 4, the value shows an increasing trend with increasing RPM. This is an expected result since faster rotation speeds require more energy consumption. A simple regression analysis indicates a strong linear correlation between averaged energy consumption per minute and spindle rotation speed (R^2 = 0.9717). Next, Figure 10 illustrates the power consumption under different settings of feed rate, with detailed experimental results as summarised in Table 5. From the figure, the power consumption pattern is somewhat fluctuating across multiple feed rates. Similar to the analysis of power consumption under multiple spindle rotation speed, actual energy consumption is calculated using the trapezoid rule, with averaged energy consumption per minute derived for the purpose of comparison. The results from Table 5 indicate that power consumption increases steadily with feed rate, which also gives a strong linear correlation value of R^2 = 0.9513. In summary, the verified power consumption results and energy analysis results for both multiple spindle rotation speed and feed rate show a strong positive relationship, which gives the possibility of predicting the energy consumption for other spindle rotation speed and feed rate using regression analysis.

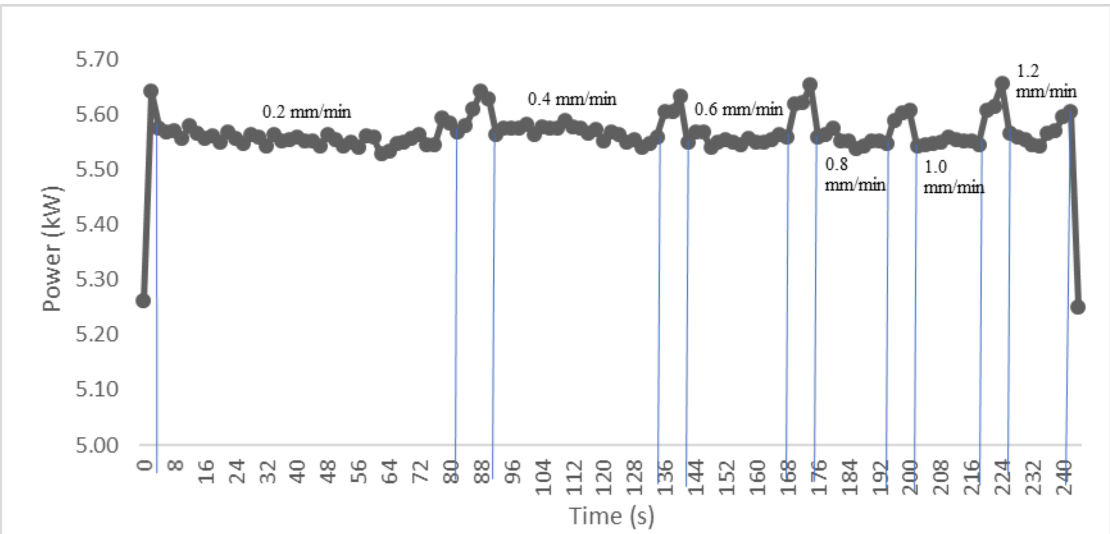

Fig. 10 *Power consumption at multiple feed rate*

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Table 5 *Summary of energy consumption under multiple spindle rotation speed*

Spindle Rotation Speed (mm/min)	Start Time (seconds)	End Time (seconds)	Average Power Consumption (kW)	Actual Energy Consumption (kWh)	Averaged Energy Consumption (kWh per minute)
0.2	4	82	5.55	0.1235	0.0950
0.4	92	134	5.55	0.0681	0.0973
0.6	142	168	5.55	0.0432	0.0997
0.8	176	194	5.55	0.0309	0.1030
1.0	202	218	5.55	0.0278	0.1043
1.2	226	242	5.55	0.0279	0.1046

4. Conclusion

This paper presents a low-cost energy monitoring device based on the Arduino microcontroller platform that has been successfully designed and developed to gauge the actual energy consumption during CNC machining operations. The device has been designed in consideration of the actual situation at the monitoring site, and upon development, the system was also successfully implemented and validated against industrial-grade clamp metres for energy monitoring purposes. The device's capabilities indicate its suitability for measuring the energy of any machine with a three-phase connection. Nevertheless, one limitation of this study is the lack of network (e.g., Internet) connectivity, which limits its functionality and usefulness as an IoT (Internet of Things) device for remote, scalable and real-time energy monitoring. For future work, the authors intended to place the device on various CNC equipment and enhance its communication via a suitable network gateway (e.g., mesh network) to gather the total energy usage at a real production site. The device will be permanently installed on the CNC machine to continuously monitor the energy usage during machining operations under various machining settings. By analysing the energy use of various devices installed on many pieces of equipment, it is possible to investigate the consumption patterns for an entire production site, which shall lead to further energy optimisation strategies. These are some of the potential areas that we are currently investigating, and shall be reported once they are ready.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *A.N. Ibrahim, S.C.J. Lim;* ***data collection:*** *A.N. Ibrahim;* ***analysis and interpretation of results:*** *A.N. Ibrahim, S.C.J. Lim;* ***draft manuscript preparation:*** *S.C.J. Lim. All authors reviewed the results and approved the final version of the manuscript.*

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