# An Investigation into Fixed Energy Consumption of Machine Tools

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**Abstract**

Improving energy efficiency of manufacturing processes requires knowledge about the energy consumption as a function of the machine tool and cutting process itself. Both theoretical and empirical models of unit process energy consumption have emphasized the relevance of fixed energy consumption which ensures the machine readiness. However, the machine tool behavior during the stand-by mode is lack of thorough study. This paper presented the investigation of fixed energy consumption from definition and description to improvement strategies. Six machine tools covering different manufacturing processes are selected for this investigation in order to evaluate the future savings.

**Keywords:**

Machine Tools; Fixed Power; Energy Consumption

## 1 INTRODUCTION

The reduction of electrical energy demands in the use phase of machine tools is an essential key to improve the environmental performance over the entire life cycle. Preliminary environmental studies for machine tools used in discrete part manufacturing (e.g. turning and milling) indicate that more than 99% of the environmental impacts are due to the consumption of electrical energy [1]. Although the use of electrical energy is crucial from the environmental and also the economic point of view, studies are primarily based on rough estimates considering averaged demands. In order to increase the reliability, case-specific energy demands of machine tool processes are presently measured and transformed into models supporting the quantification of energy demands [2]. Traditional estimation of cutting energy for turning and milling processes is based on process parameters, which has been a starting point for the optimization of machining processes under energetic aspects as well as the derivation of capacity requirements for the machine tool [3]. As this method is restricted to the cutting process and solely capturing the energy for material removal, the unavoidable energy demand ensuring an operational readiness of the machine tool is yet disregarded.

Recent theoretical exergy framework and empirical models of unit process energy consumption have emphasized the relevance of fixed energy consumption which ensures the machine readiness [4-5]. More importantly, the fixed power demands continuously accumulate the total energy consumption throughout the work shift. However, the machine tool behaviour during the stand-by period is lack of thorough studies.

This paper investigates the energy consumption of the machine tool for reaching and remaining operational readiness. The initial point therefore is the definition of a fixed power demand of a machine tool. Starting from this definition, the fixed power demands of six machine tools covering three different manufacturing processes are physically measured and analysed. The fixed power demands are described on a component basis by considering the machine configuration and given power demands of components. Within the detailed information, the energy requirements of machine availability are discussed as an enabler to promote energy efficiency of machine tools.

## 2 FIXED ENERGY DEMAND OF MACHINE TOOLS

### 2.1 Definition of Fixed Energy Demand of Machine Tools

The energy consumption of a machine tool results from the temporal power demand which is not static but rather dynamic throughout a machining process. It is influenced by the design of the process and the selected machine tool. Power meters enable to capture the specific power demand of a machining process which consequently provides a basis to recognize actions (e.g. acceleration of spindles). Reviewing the power profile of an exemplary turning process in Figure 1, the start-up of the machine, spindle and material removal as well as the resulting power states can be determined [4]. With consideration of these states the power demand can generally be differentiated into a variable and a constant portion [5].

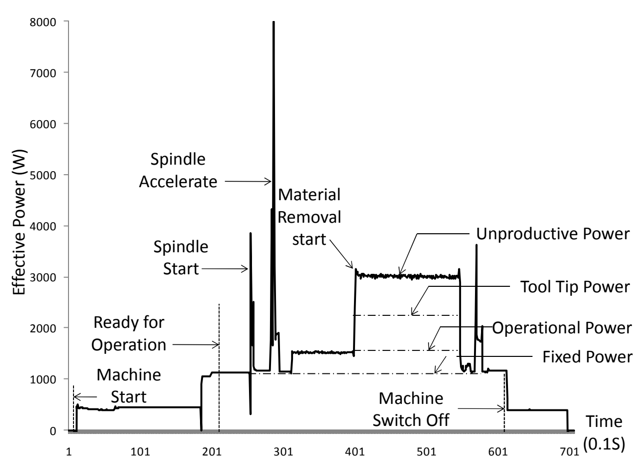


Figure 1: Power profile of a turning process [4].



J. Hesselbach and C. Herrmann (eds.), *Glocalized Solutions for Sustainability in Manufacturing: Proceedings of the 18th CIRP International Conference on Life Cycle Engineering, Technische Universität Braunschweig, Braunschweig, Germany, May 2nd - 4th, 2011*,
DOI 10.1007/978-3-642-19692-8_47, 

The variable power considers the process-related demand to conduct the machining operation. This includes not only the power required for removing material but also the process-depended operation of components (e.g. spindle rotation and movement of axis). Apart from that, the constant power demand resumes the fixed, machine-related power ensuring a functional mode of operation (ready for operation) [3]. While the variable power aggregates the power demand of motors and spindles enabling the material removal, the fixed power demand also includes the power demand of operating components as motors and spindles [6]. These devices are energized to maintain in position. With regard to components and supporting a better understanding of the power demands (see Figure 1), an extension to the given power classification is proposed considering the following four power segments [4]:

- *Fixed power*: power demand of all activated machine components ensuring the operational readiness of the machine tool;
- *Operational power*: power demand to distinctively operate components (e.g. move axis or rotate spindle) enabling the cutting as performed in air-cuts;
- *Tool tip power*: power demand at tool tip to remove work piece material;
- *Unproductive power*: power converted to heat mainly due to frictions during the material removal.

### 2.2 Technologies of Reducing Fixed Energy Consumption

As mentioned before, the fixed energy consumption is highly relevant for reducing energy consumptions of manufacturing processes throughout different machine states. Different energy efficiency measures aim at reducing the fixed energy demands through improved machine tool design as well as optimized process design.

From the machine tool builder's perspective, the improvement of machine tool design includes for instance from substitution of inefficient electrical motors to use of break for non moving axes [1]. As a result, the instantaneous fixed power could be minimized.

For the existing manufacturing plant, process control measures enable the optimal utilization of the process by eliminating non-value adding tasks. However, standby state of each machine tool is unavoidable in most scenarios. The smart energy saving technologies has thus been introduced by control suppliers such as DMG Energy Save, which automatically power off or switch machine tool into hibernate mode once the standby period exceed a customer defined limit [7]. In order to achieve an optimal result, the configuration of the smart control system requires detailed information about machine readiness and availability. Therefore, the energy requirements of ensuring operational readiness are focused in this paper.

### 2.3 The Energy Index for Machine Readiness and Availability

As shown in Figure 1, machine tool passes different state to achieve operational readiness. During this period, machine tool not only consumes electrical energy but also requires a certain amount of time to achieve operational readiness. The same situation is applied to machine power-off stage. Therefore, the following energy related indicators are selected for evaluating machine readiness and availability.

- *Peak Power*: maximum instantaneous power requirement during the start-up period, which is relevant to the additional energy cost due to power peaks.
- *Time for operational readiness*: duration from machine start-up until all the indispensable components are activated to ensure operational readiness.
- *Energy consumption for start-up*: the total energy consumption during the start-up period.
- *Fixed power*: as defined before, it can be used to estimate energy consumption of remaining machine availability.
- *Time for machine power-off*: duration from machine switch-off until every component is inactivated.
- *Energy consumption for power-off*: the total energy consumption during the power-off period.

## 3 DESCRIPTION OF FIXED POWER DEMAND

In order to derive the energy index of machine readiness and availability, energy metering and monitoring is essential to obtain authentic information of each individual machine. It requires a high resolution to capture the instantaneous power peak and the rapid changes of machine states. Therefore, the sample rate should be less than 0.5s.

A component-based description of fixed power consumption is also important to offer insights of machine behaviour. The starting point is to identify all the electrical components as well as their characteristics. Then, the constitution of the fixed power should be described. Preliminarily, Others like Dietmair et al used finite approach to assign the energy consumption to each component according to different operation sequences [2]. However, only the hydraulics can be quantified based on observed energy curve. Owing to the physical constraints of power measurement at a component level, alternative information resources were utilized, such as wiring scheme. It should be noted that the rated power given in machine documentations is an estimated value under either nominal or extreme conditions, which initially indicates the capacity of the electrical motor. Therefore, the calculated fixed power breakdown is compared with real data to provide approximate information of each component.

The analysis comprehends six machine tools covering three different manufacturing processes (Table 1).

| Machine tool | Type |
|---|---|
| Studer S40 | Universal grinding machine (3 spindles) |
| Studer S120 | Internal grinding machine (1 spindle) |
| Colchester A50 | CNC lathe (1 spindle) |
| MS NL 2000MC/500 | CNC lathe with milling functionality (2 spindles) |
| MS Dura Vertical 5100 | Vertical milling machining centre (1 spindle) |
| DMU 60 P | 5-axis milling machining centre (1 spindle) |

Table 1: Machine selection for conducting the study.

### 3.1 Experimental Measurements of Fixed Energy Consumption

For each of the above listed machine tools, the power demand was measured at the main switch with a National Instrument (NI) system, which is developed on a LabVIEW interface in conjunction with a NI data acquisition device. The voltage and current signals are captured and recorded every 0.1 second via NI module 9225 and 9229 respectively. Three Fluke current clamps were applied to convert current signals into voltage signals. The captured signals are processed simultaneously to the LabVIEW interface via NI compact chassis Cdaq-9172. The power measurement started from turning on the main power switch until each machine tool was ready for operation. The above measured period varies in terms of duration due to different start up procedures. Although the power consumption during standby-mode fluctuates within a small derivation, the fixed power is relatively static comparing to machine start-up and operation periods. In order to indicate the power behaviour, the start-up to operation for each device is illustrated in Table 2.

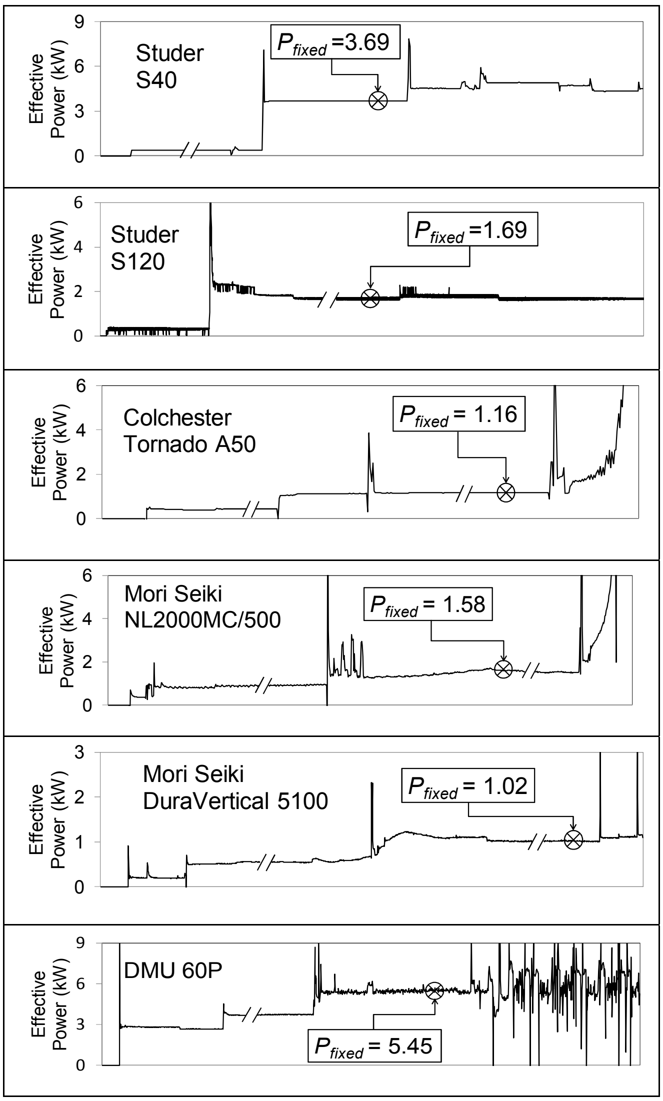


Table 2: Measuring fixed power for each machine tool.

### 3.2 Deduction of Fixed Power Demand

Machine tools can be characterized as assemblies of components ensuring a specific function [6]. Each component performs a particular act enabling the entire machine to perform more complex, useful functions. Table 3 summarizes briefly the individual functions of electrical components in machine tools which can generally be classified into spindle drives, servo drives, hydraulic system periphery system, cooling and lubrication system, control system and auxiliary system [3].

Based on the operation of components, the power profile of a machining process represents the accumulation of the individual power demands for each component (see Figure 2). The research scope is limited to a machine tool with its integrated components; disregarding additional peripheral devices as coolant filter systems. Other components, such as coolant pump motor, chip conveyer motor, and tool library systems are only activated when they are commanded during processing stage. In this case, they are thus excluded for fixed power description.

| | Component | Function |
|---|---|---|
| Spindle Drives | Main Spindle Motor | Besides rotary motion, holds as well as centres work piece |
| | Rotary Tool Spindle Motor | Rotary motion for cutting tool |
| Servo Drives | *i*-Axis Motor | Linear motion for cutting tool towards *i*-axis |
| | Tailstock Spindle | Besides rotary motion, holds as well as centres work piece at tailstock |
| | Turret Motor | Rotary motion for cutting tool change |
| Hydraulic System | Hydraulic Unit Motor | Rotary motion for pump to supply clamping pressure |
| Cooling Lubrication System | Lubricant Pump Motor | Rotary motion for pump to supply lubricant |
| | Oil Cooler Pump Motor | Rotary motion for pump to supply oil cooler circuit |
| Control System | Spindle Amplifier/ Frequency Converter | Transfer numerical control signal for spindle rotation speed into adjusted electrical signal |
| | Servo Amplifier /Frequency Converter | Transfer numerical control signal for servo feed into adjusted electrical signal |
| Auxiliary System | Computer and Display | Processing and visualization of program |
| | Lightning | Lightning the working area |
| | Fan | Air flow generation for cooling electrical components |
| Periphery System | Coolant Pump Motor | Rotary motion for pump to supply coolant circuit with pressure |
| | Chip Conveyer Motor | Rotary motion for chip conveyer |
| | Tool Change Arm Motor | Rotary motion for tool change |

Table 3: Electrical components in machine tools.

Considering the power characteristics of components two types can generally be identified. The first type considers components that are either fully activated or not. The auxiliary components are generally under this category. Although the power demand of hydraulic pump depends on the desired pressure, the oil pressure remains constant throughout the stand-by and processing stages. The change of hydraulic pressure only occurs when unclamping the chuck. Hence, the hydraulic system can be classified as a static component. The same reason can be applied to cooling and lubrication system due to the continuous operation with a constant load. The second type covers components that are operated with a dynamically adjusting load. Generally, the spindle and servo motors rotate at variant speed. The dynamic torque and load on the drive system requires frequent adjustments [8]. The power demands for the control system (e.g. frequency converter) thus vary accordingly. Therefore, the spindle drives, servo drives and associated control system are grouped as adjusted components, as illustrated in Figure 2.

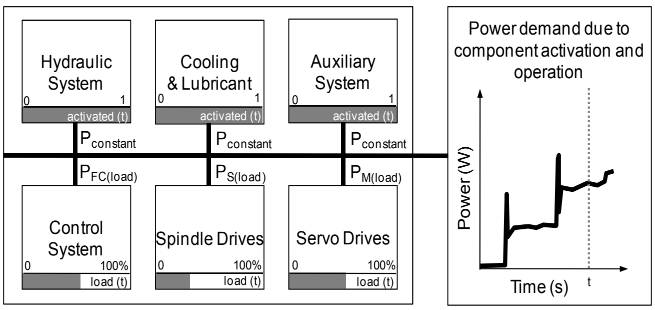


Figure 2: Power agglomeration of components to the power demand of the machine tool.

### 3.3 Component-based description of Fixed Power demand

Physical measurements at a component level require access to each sub-system. Conventional energy metering system can only capture the voltage and current data with constant frequency, which is not suitable for the devices with variant frequency such as amplifier, frequency converter and servo drives. The metering point at the main switch also limits the transparency of machine behaviour, since only significant power changes can be detected from the observed curve.

| Category | Component | Rated Power (kW) |
|---|---|---|
| Auxiliary System | M1 Cross Slide Fan | 0.040[10] |
| | Spindle Motor Fan | 0.020[10] |
| | Lightning | 0.036[10] |
| | Computer and Display | - |
| Hydraulic System | Hydraulic pump motor | 0.550[10-11] |
| Cooling and Lubrication | Cooling Pump | - |
| | Lubricant Pump | - |
| **Sub-total** | **0.646** | |
| Control System | Spindle Amplifier Module | 0.120[12] |
| | Servo Amplifier Module | 0.093[12] |
| Servo Drives | X-Axis Servo Motor | 0.500[10-11] |
| | Z-Axis Servo Motor | 0.500[10-11] |
| | Turret Servo Motor | 0.300[10-11] |
| Spindle Drive | Spindle Motor | 5.500[10-11] |
| Periphery | Coolant Pump | 0.370[10] |

Table 4: Rated power list of each component in Colchester A50.

Instead of relying on real time measurement, the wiring scheme, circuit diagram and machine specifications were utilized for the fixed power estimation of each component. According to EN 60204 wiring schemes document integrated components as well as their power demand in detail in order to facilitate awareness about safety, function and maintenance of electrical equipment used in machines [9]. Thus, the power demand of components at nominal operational conditions can easily be derived for these documents. With other documents (e.g. circuit diagram, machine manuals), the rated power or nameplate power can be obtained for the major electrical components. This given value is the power output of a device under specific or nominal operating conditions, which indicates the capacity of each motors and drives with a continuously load [8]. Table 4 is an exemplary list of component rated power for Colchester A50.

For most of the tested machines, all the static systems are activated, such as hydraulic system, auxiliary system, cooling and lubricant system. The hydraulic, cooling and lubrication system have been identified as the main electrical consumers for machine readiness. For those major components, the rated power values highly agree with real measurements. For instance, the hydraulic pump of Colchester A50 is rated as 0.55 kW. The power curve of machine start-up indicates a significant power increase due to hydraulic activation from 0.45kW to 1.05 kW. Another example is for the complex 5-axis machine centre DMU 60P. The cooling unit normally remains idle until the temperature exceed a certain degree, while the power demand increases from 5.45 kW to 6.8kW. The rated power values of all the cooling components which includes compressor, pump and fans sum up to 1.25 kW.

However, the aggregation of available rated power of static components (e.g. 0.646 kW) does not fit the real measurements (e.g. 1.16 kW). The differences are mainly due to following reasons:

1. Lack of information about several components;
2. Difference between input power and output power;
3. Disregards the adjusted power demand for the servo drives and the control system.

For some reviewed machines, the rated power is not provided for each electrical component. Generally, the machine specifications only include the nameplate power for the main drive motors. As shown in table 4, the energy related information for computer, cooling and lubricant system is yet absent. Certainly, the input power is not equal to output power as the energy transmission efficiency is constantly less than 1. In addition, the rated power is estimated under nominal operating conditions which may not be the same situation as machine standby. Nevertheless, the difference is relatively small as the static components operate under constantly low load. Apart from the components with constant power demand, the servo motors and the associated control system are also activated [13]. For the turning and milling machine tools, the servo motor holds the cutting tool at the home position against the gravity of the cutting tool, which requires the servo motor constantly adjusting the tool position with relatively low loads. The servo amplifier or associated frequency converters are hence activated accordingly. However, the specific loads on the servo motors are unlikely to be quantified, especially during the stand-by stage. The self-consumed electrical energy of frequency converters or amplifiers is even more difficult to derive. The further investigation of the Fanuc amplifier (used for Colchester A50) showed that the heat dissipation of the servo amplifier is 93W under normal operational loads [12]. Since the servo motor is only positioning, all the rated power demands of servo motors and associated control units are scaled down accordingly.

By comparing the experimental power demand at different machine states with the rated component specific power features, a component-based description of fixed power demand is therefore obtained, as summarized in Figure 3 [10-12, 14-19].

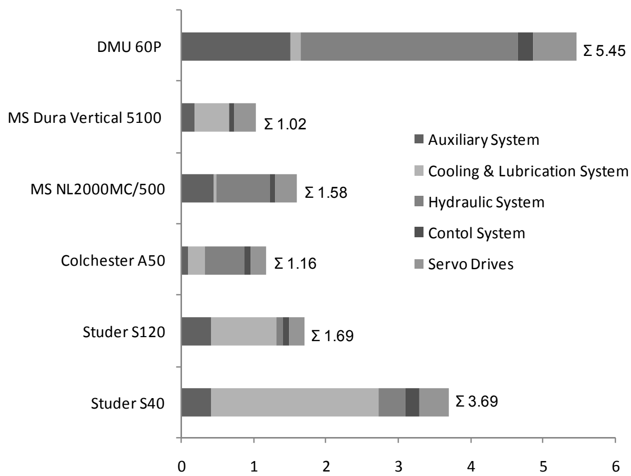


Figure 3: Component-based description of fixed power consumption.

## 4 STRATEGIES FOR FIXED ENERGY REDUCTION

Energy consumption reduction generally includes two strategic approaches. One is by reducing the instantaneous power demands, which requires an energy oriented design of machine tool at a component-base; the other one is by shortening the period of fixed power integration, which can be achieved by both increasing machine utilization as well as switching-off the machine to reduce the standby time.

To practice above energy saving strategies, it is essential to acknowledge the energy performance of the machine tool during start-up, standby and power-off stages. However, the existing machine documentations do not provide sufficient information for energy consumption estimation. Moreover, energy metering and monitoring of each individual machine is time consuming and costly. Generally, it requires 1.5 hours for applying the metering system, measuring the process and analyzing the data with hourly costs of US$50. The initial installation cost is even more expensive since specialized and certified technician is required for connecting the high voltage. For a large plant, there are normally hundreds machine tools differentiating from age to capacity. It is nearly impossible to derive energy profile for each individual machine tool. In order to avoid further physical measurements at machine level, it is important to include power demand of the electrical consumer at different stages in the machine manuals.

### 4.1 Componented-based improvements of fixed power demands

A reduction of fixed energy consumption can directly be achieved by technical measures that reduce the fixed power demand of components through applying energy efficient devices. Figure 4 illustrates average fixed energy breakdown of the reviewed machine tools. It suggests that the improvements of hydraulic system, cooling and lubrication system can save up to 58% of fixed energy consumption.

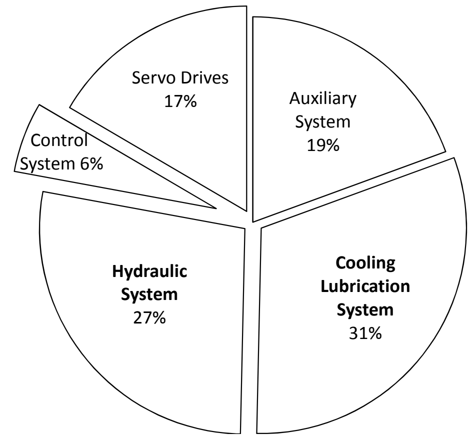


Figure 4: Average fixed energy breakdown of reviewed machine tools.

The self-regulatory initiative lead by Cecimo has listed potential measures for energy improvements of machine tools. For instance, the hydraulic unit and cooling lubricant unit are suggested to be coupled with control system, and be activated only on operating stage. For the auxiliary units, the line connected motors can be replaced by inverter motors. The feed axes during non moving axes should be also switched off and clamped by a brake [1].

In order to precisely estimate the leverage of the energy efficiency measures, the component-based description of fixed power consumption needs to be improved in terms of its authenticity and level of detail.

### 4.2 Process optimization for reducing fixed energy consumption

As mentioned earlier in this paper, the fixed power adds the total energy throughout different machine states. Different strategies should be applied according to the status of the machine tool.

During the operation stage, the fixed power sets the power base for functional performance. According to the studies about specific energy consumption (SEC), the share due to fixed power consumption (specific fixed energy) can be reduced by increasing the process rate [4]. In other words, a higher production speed results less fixed energy consumption per product.

For the non-continuous manufacturing processes, such as turning and milling, the standby time is unavoidable but feasible to be minimized. The main strategy here is to switch-off the machine if standby time is long enough. It is critical to notice the functionality of the fixed power, which ensures the machine readiness for operation. Once the machine is completely switched off, a specific time is needed to regain operational readiness. Therefore, the energy saving measures should not sacrifice the availability of the machine tool.

As defined in section 2.3, the energy related index is compared among selected machine tools (see in Table 5). The study cycle starts from machine power-off until the machine readiness is retrieved. A 30 min idle period is assumed for the comparison between temporarily switching off the machine and keeping machine standby.

| | Studer S40 | Studer S120 | Colchester A50 | MS NL2000MC/500 | MS Dura Vertical 5100 | DMU 60P |
|---|---|---|---|---|---|---|
| Peak power (kW) | 9 | 6 | 4 | 9 | 2.4 | 9 |
| Time to power-off (s) | 15 | 10 | 10 | 15 | 10 | 15 |
| Energy to power-off (kWh) | 0.012 | 0.004 | 0.001 | 0.005 | 0.002 | 0.025 |
| Fixed Power (kW) | 3.69 | 1.69 | 1.16 | 1.58 | 1.02 | 5.45 |
| Time to standby (s) | 250 | 110 | 30 | 150 | 110 | 100 |
| Energy to standby (kWh) | 0.256 | 0.036 | 0.004 | 0.038 | 0.021 | 0.096 |
| Total Energy Cost for Temporary Switch Off (kWh) | 0.268 | 0.040 | 0.005 | 0.043 | 0.023 | 0.121 |
| Energy Saving if machine idle for 30min (kWh) | 1.577 | 0.805 | 0.575 | 0.747 | 0.487 | 2.604 |

Table 5: Comparison of energy index of machine readiness.

Firstly, the peak power has been detected during the machine start-up period. Although the peak value is less than the spindle acceleration or other rapid changes of motor states, this instant drawing current may cause additional energy cost due to grid quality. The time from machine power-off to standby differentiates among the reviewed machine tools. While grinding machine Studer S40 requires 3.5 mins for pre-lubrication, the Colchester A50 can regain operational readiness in half minute. When applying an automatic energy saving system, the default switch-off time should be selected according to the cycle-time from machine switch-off to standby. Based on the assumed scenario, the machine tool with high fixed power demand, such as DMU 60P, Studer S40, can result significant savings by temporally switch-off the machine.

It should be noted that the machine is completely powered off in this estimation. Recent technologies may allow machine to be easily restarted through the receipt of the familiar emergency shut-off operating mode [7]. Both power-off and hibernate mode requires customized analysis of fixed power consumption. Since the energy saving device cost more than ￡1,099 pre device, the cost efficient estimation should be also included in practice.

## 5 SUMMARY

This paper presented the investigation of fixed energy consumption from definition and description to improvement strategies. The awareness of fixed power demands have been raised due to the considerable share of the total energy consumption. While physical measurements derive the authentic power behaviour during different machine states, the machine documentation should also provide sufficient information of energy consumption to improve the transparency of the machine tool. The strategies for fixed energy reduction are discussed and evaluated considering both machine design measures and operational process optimizations.

## 6 ACKNOWLEDGEMENTS

The lead author kindly acknowledges the funding provided by the Advance Manufacturing Cooperative Research Centre for this research. This paper was compiled by the Joint German-Australian Research Group “Sustainable Manufacturing and Life Cycle Management” funded by the BMBF under reference AUS 09/AP1 and managed by the International Bureau of the BMBF at DLR.

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