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Increase in energy efficiency of industrial production processes through thermal crosslinking of cutting-machine tools and cleaning machines by heat-pump technology

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Abstract

The research project “ETA-Fabrik” focuses on improving the energy efficiency in the context of industrial production processes by developing a holistic view on the energy requirements of individual production systems (production machines, building services and construction) and systematically optimizing their interdependencies. In the field of machining, up to 30 % of the energy requirements are spent on cooling processes for cutting-machine tools and up to 50 % are spent on heating the medium tank of an aqueous parts cleaning machine. One optimizing approach to improve the energy efficiency is the reutilization of waste heat from the cooling medium of the cutting-machine tool by raising the temperature level of the medium using a heat pump. A test rig has been developed and built up to demonstrate the potential of this solution. A variety of experimental scenarios resulted in an increase of energy efficiency of at least 43 %. In order to ensure practical relevance, the operating scenarios based on real process chains are analyzed by including the machinery as well as the produced parts. Additionally, the economic efficiency is ensured by the use of standard modules without accepting any compromises in functionality. The thermal crosslink includes the utilization of solar-thermal storage to provide heat transfer and allows the temporal decoupling of the operating machines. This test rig is a prearrangement and test setting for the crosslink of the whole factory with additional recuperation and storage technologies.

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Keywords: Energy efficiency; Water/water heat pump; Crosslinking; Machine tool; Aqueous parts cleaning

1. Introduction

1.1. Challenges for industrial production systems

From 1990 to 2013 the worldwide total primary energy supply increased by more than 50 % [1] with well-known side effects, like global warming and turn into political objectives worldwide. The final global pact of the 2015 United Nations Climate Change Conference, a consensus agreed by 196 countries (the “*Paris agreement*”) and acknowledges the necessity to reduce carbon dioxide emission [2]. Germany has a pioneer role due to the political decision to force the energy transition [3]. An important element of this strategy is the increase of energy

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efficiency in the industrial sector [4]. This becomes more important by the increased worldwide energy consumption.

The inclusion of process heat is indispensable to achieve target efficiency measures. In 2012 approximately 1,673 of totally 1,923 Petajoule supplied process heat were used in the industrial sector [5]. Large quantities of the heat are lost after the actual processes [6], and, thus, the potentials of heat recovery are huge. One necessary requirement is crosslinking heat sources and sinks in production systems. Potentials to increase energy efficiency up to 40 % are given by linked production systems [7]. However, various barriers prevent a comprehensive implementation of such measures, i. e. missing experience or knowledge, complexity of the technical systems and mismanagement [6].

1.2. Concept of ETA-Factory

The Institute of Production Management, Technology and Machine Tools (PTW) initiated with 39 research partners the research and demonstration project “ETA-Fabrik” (Energy efficiency, Technology, Application Centre [8]. Within this project, representative metalworking production plants are analyzed and optimized regarding energy efficiency aspects to achieve the goal of increasing energy efficiency in industrial manufacturing systems. Here a machine component of our partner Bosch Rexroth serves as reference process chain. The production plant includes

- A turning and grinding center,
- Two alternative cleaning processes and
- A heat treatment (gas nitration) process.

The goal is not exclusively to improve the energy efficiency of single production plants, but to enable their energetic crosslinking and to provide inevitable waste heat for other processes with heat demand. Likewise, the production equipment, the machine periphery, the building technology and the factory building are included in the considerations. New energy efficiency potentials arise from the crosslink of heat sources and sinks to ensure a use of waste heat in the production environment. While the waste heat from the heat treatment equipment can be used to heat the cleaning baths or to generate cold through sorption technology, the manufacturing building is a heat sink for low temperature waste heat. Additionally, the building can be utilized to generate cold water through heat transfer with the environment or to provide solar thermal heat. The developed measures will be put into practice in a new research and demonstration building at TU Darmstadt, shown in Fig. 1.



Fig. 1. Research and demonstration building “ETA-Fabrik”; Source: ETA-Fabrik / TU Darmstadt / Eibe Sönnecken, Jan Hosan

One prime example of crosslinked production machines, is the reutilization of waste heat from the cooling fluid of a cutting-machine tool. By raising the temperature level of cooling fluid with a heat pump. The medium of an aqueous-cleaning machine can be heated. A schematic of the test rig in the ETA-Factory is shown in Fig. 2. In the following the cleaning process, the cutting-machine system and the improved energy balance are described in detail.

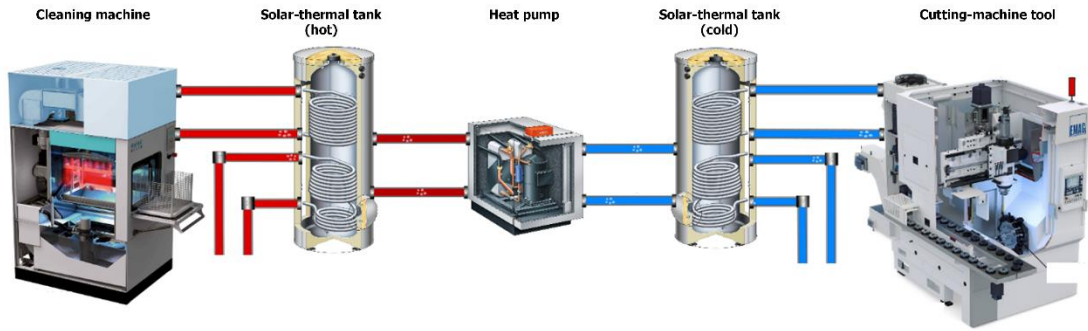


Fig. 2. The test rig of a crosslinked system built up in the *ETA-Factory*. Elements from left to right: aqueous-cleaning machine, solar-thermal tank (hot side), heat pump, solar-thermal tank (cold side), cutting-machine tool

2. Characteristics of aqueous cleaning

2.1. Parts cleaning

Part cleaning processes are commonly used in the metal processing industry. In process chains there are multiple reasons for part cleaning operations [9]:

- Mechanical manufacturing, e.g. before machining, assembly, measurement, packing
- Before surface treatment, e.g. electroplating, coating
- Before heat treatment
- Maintenance and repair

These various types of contaminations cause different tasks of cleaning processes which require a specific treatment. Lubricants, coolant, grinding paste, inhibitors, solid particles, rust, oxides, old coatings and numerous combinations can be found [10]. In accordance to these diverse cleaning tasks many different cleaning processes are necessary to achieve the required results. Aqueous and, in particular, spray or immersion cleaning are the processes mainly used, by manufacturers and end users [11]. In almost nine out of ten interviewed companies aqueous cleaning processes are applied of which over 50 % use immersion and spray cleaning methods. In this work, the most common applications of cleaning processes are examined in order to ensure a high transferability.

2.2. Cleaning machine and process

A standard machine for spray cleaning processes is used for further studies. The central element is the cleaning chamber with a rotating basket system for different kind of parts in a batch production system. A two-step filtration system removes swarfs and small particles with diameters larger than 100 μm . An electrical heating system is installed in the process water tank. It balances the heat losses caused by the heating of the parts with ambient temperature and the surface heat losses of the machine, which are shown in Fig. 3 a).

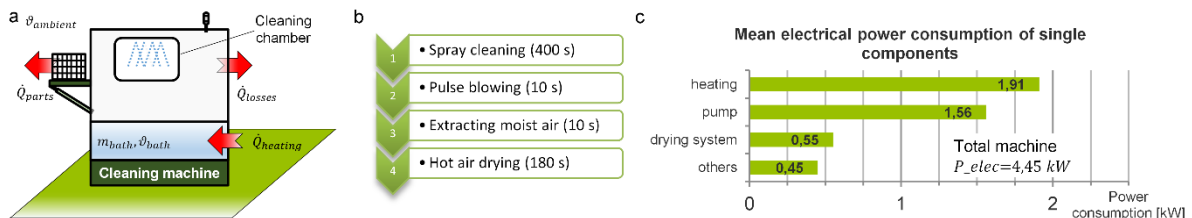


Fig. 3. (a) Heat flows of a cleaning machine, (b) Applied cleaning process, (c) Average electrical power demand of a cleaning process

The cleaning machine has an integrated hot air drying system which prevents corrosion through residuals of process water. The defined cleaning process in combination with a batch mass of 25 kg results in an electrical power consumption on component level as given in Fig. 3 c)

The temperature of the cleaning bath is $\vartheta_{bath} = 60^{\circ}C$. The majority of the heating power is needed to compensate the heat losses $\dot{Q}_{losses} = 1.18 kW$. The rest is needed to warm up the part mass for every new batch. The mean electrical power demand for one cleaning process (for process details and timings see Fig. 3 b)) results in a total energy demand of $0.80 kWh$. Detailed technical specifications needed for further examination are shown in Table 1.

Table 1. Technical specifications of the cleaning machine

Specification	Value
Tank volume	320 l
Heating capacity	10 kW
Spraying pressure pump	
Volume flow	200 l/min
Pressure	2.0 bar
Hot-blowing drying system	
Volume flow	160 m ³ /h
Max. temperature	90° C

2.3. Media in aqueous cleaning processes

The most important factor which influences the heat exchange conditions is the used cleaning medium. Depending on the different tasks of the cleaning processes and the types of contaminations, the heat-transfer medium consists of a mixture of many different ingredients. Typical cleaning media like cleaning active agents, polyphosphates, inhibitors, corrosion protection, emulsifiers, stabilizers, biocides are listed in [10]. Relevant for the heat exchanging process are in particular solid particles in combination with liquids of higher viscosity and saponification effects. This results in a large propability of fouling on heat transfer surfaces [12] and constitutes the major challenge to ensure the functionality of the heat exchange.

3. Characteristics of machining

3.1. Turning

Turning is a basic machining process in the metal processing industry. Round workpieces are machined with tools from raw material. The optimum machining process can be achieved by the interaction of

- Workpiece material,
- Tool material,
- Cooling Lubricant,
- Cutting Speed and
- Feed Rate.

Typical function modules of turning machines concerning the energy demand and optimization are

- Electrical drives (main spindle and axis),
- Cooling lubricant system (low and high pressure pumps, filter elements),
- Hydraulics (pumps, valves),
- Chiller (pumps, compressor, fans),
- Pneumatics and
- IC Technologies.

Starting point of an energy optimization is the measurement of the electrical power consumption of the machine tool and its single function modules in a particular machine state. An established classification [13] distinguishes the machine modes working, operational, powering up, standby and off.

Energy optimization of machine tools has been the topic of numerous research projects in the field of machining production in recent years. One prime example is the optimization of the 5-axis machining center MAG XS 211 that was re-designed within the research project “Maxiem” to become more energy efficient taking into account a desired payback period on investment of three years [7,14].

Measurements within the research project “ETA-Fabrik” at EMAG VL 2 machines as well as the investigations demonstrated that the energy demand of the machine tool cooling system is significant [15,16]. Independently of the used technology all the approaches tried to minimize the energy demand for the heat transfer and dissipation of the cooling system. In those considerations of single machines, the potential of waste heat recovery, which is discussed in this work, was not taken into account.

In the stock removal process only 0.1 to 6.5 % of the electric power consumption remain in the crystal lattice due to material separation and plastic deformation [17]. The main part of the energy is converted through numerous conversion processes, which are associated with losses (e.g. friction), into non usable forms of energy like waste heat. One part of the waste heat can be collected in the internal cooling system, whereas the rest is emitted to the environment (conduction, convection, radiation). Results of the energy demand and waste heat recovery by thermal crosslinking are presented in the following section.

3.2. Machine tool and process

At the vertical turning pick-up machine EMAG VLC100Y of the test rig presented in Fig. 2 a large amount of the waste heat is collected in the water based cooling system of the main spindle, turret and the control cabinet. The following results were determined by a reference process of machining of a hydraulic pump workpiece in two operation steps (time/workpiece: 380 s) and a continuous operation of 8 hours (2 % Standby, 20 % Operational, 78 % Working). As shown in Fig. 4, the average electric power demand in this test setup sums up to 5.8 kW.

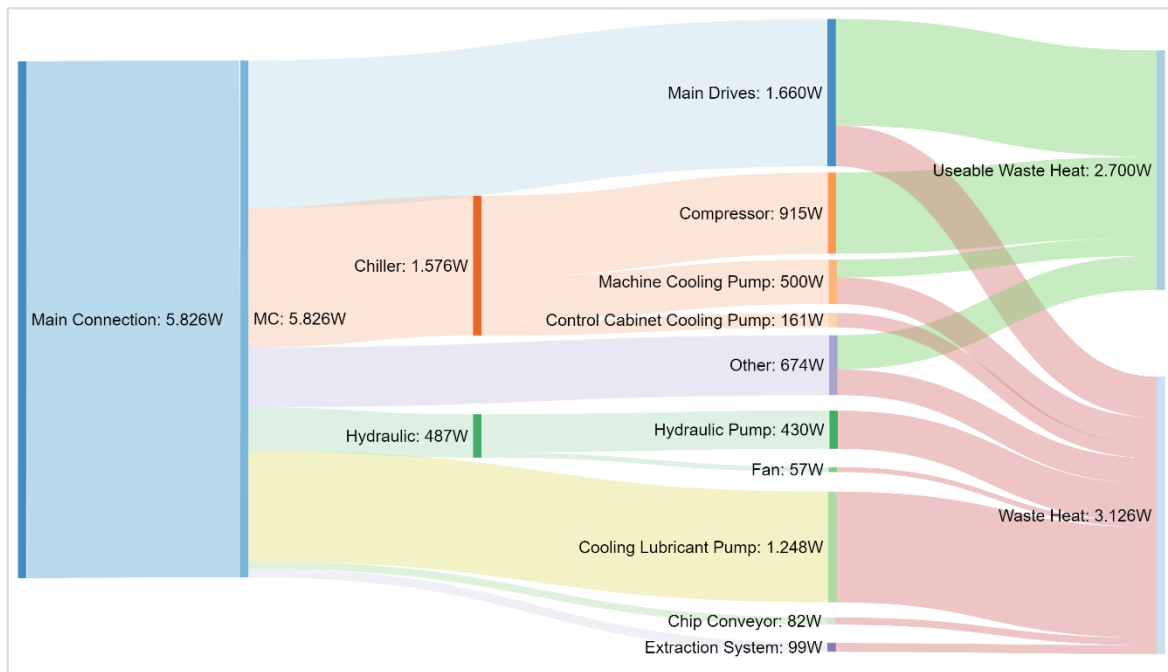


Fig. 4. Average electric power demand of EMAG VLC100Y in machine mode “Working”

The useable average thermal waste heat, which is transferred via an external cooling system and stored in the cold water tank, sums up to 2.7 kW. The reutilization is described in the following chapter.

4. Technical requirements for crosslinked production machines

4.1. Using waste heat by water/water heat-pump technology

The used heat pump is a *Vitocal 350-G* from *Viessmann GmbH Co. KG* with an estimated heat output of 7.3 kW and a refrigerating capacity of 5.83 kW. This high-temperature heat pump reaches a flow temperature of up to 72° C. It uses an EVI (Enhanced Vapour Injection) refrigerant circuit, in which the refrigerant is first cooled by vapor and then compressed. The RCD (refrigerant cycle diagnostic) system continuously controls the refrigerant cycle to ensure high efficiency [18]. Here, the primary circle of the heat pump produces the process heat for the cleaning machine and the secondary circle the coolant heat flow for the cutting machine.

4.2. Solar-thermal tank: a functional combination of temporal decoupling and heat exchanger

Due to the temporal displacement between waste heat of the cutting machine and heat demand of the cleaning machine a thermal storage is necessary. For this setup two *Vitocell 300-B* 500 liter tanks were used. These kind of storages are state-of-the-art product and can be integrated in many different types of crosslinked energy systems. In addition to the functionality of temporal decoupling, the solar-thermal tank also applies the heat exchange through a coil tube which physically decouples the fluids of the machines from the heat pump circuit. These kind of storage The technical specifications are shown in Table 2.

Table 2. Technical specifications of the water tank including the heat exchanger

Specification	Value
Tank volume	500 l
Heating area of the coil tube	1.45 m ²
Inner diameter of the coil tube	31.75 mm
Outer diameter of the coil tube	35.00 mm
Length of the coil tube	13.20 m
Mean curvature radius of coil	0.23 m

4.3. Technical equipment for connections

The cold side of the system uses insulated plastic piping. The hot water tank is connected with the cleaning machine bath and the heat pump via insulated stainless steel piping. Sensors determine pressure and volume flow rate in the heating flow of the coolant. Speed-controlled pumps circulate the water between the different vessels. An industrial stainless steel pump is used between the solar-thermal tank and the cleaning machine to circulate the partly polluted water.

5. Efficiency potential of crosslinked production systems

5.1. Measurement and test program

In order to evaluate the limitations and performance of the system under high stress, an artificial cleaning program was created, which simulates a high load on the cleaning machine. This cleaning program contains a long time period of suctioning moist air out of the machine to create an unusual large demand of heating for this size of cleaning machine. The energy demand of the single machines without crosslinking is shown in Fig. 5.

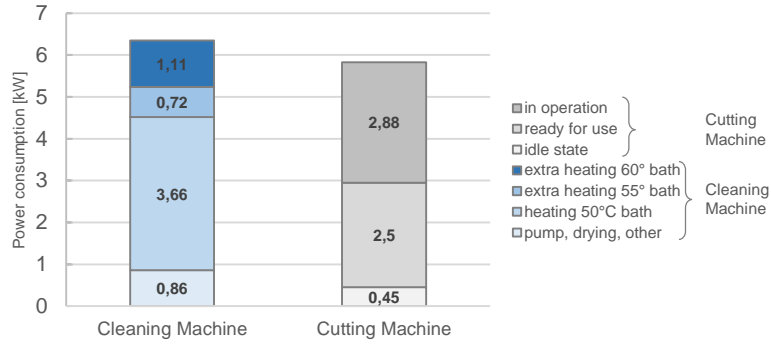


Fig. 5. Electrical power consumption of the cleaning machine (left bar) and cutting machine (right bar)

Additionally, pumps, dryers and other components like control units have an average consumption of 0.86 kW. The largest fraction of it is needed for the heating plates for internal bath heating. In order to keep the temperature of the bath at 50° C during operation 3.66 kW are necessary. A higher bath temperature demands an increase in power consumption. A bath temperature of 55° C results in an increase of 0.72 kW electric power and another increasing to 60° C needs additional 1.83 kW compared to the 50° C setting. This increasing power consumption can be explained by the increased temperature difference between bath and ambient.

5.2. Performance of the crosslinked system

In the next step, the power consumption at different temperature stages of the crosslinked system was measured. In order to ensure stable conditions, a temperature difference of 10 K between the bath of the cleaning machine and the hot water tank turned out to be necessary. One of the key performance indicators of a heating pump is the COP. The COP is the ratio between the provided heat Q and the required electrical power P for operation

$$COP = \frac{|Q|}{P} \tag{1}$$

In the test setup, the heating output was measured by comparing the fluid flows from and to the heat pump during the test period. The thermal energy input to the bath of the cleaning machine was determined to evaluate the overall system performance. This energy was used in equation (1) as usable heat Q to determine the systems COP.

The heat pump reached a COP of 2.8 for a hot tank temperature of 60° C and cold tank temperature of 12° C. The COP under considerations of losses between heat pump and cleaning bath is reduced to 2.63. At all bath temperatures the electric energy consumption was reduced up to 50 %. Besides the overall performance, the system was also analyzed for different combinations of hot and cold tank temperatures. As discussed in the previous section, the hot storage temperature was always kept 10 K higher than the cleaning bath temperature which is a reference variable in the thermal crosslinking.

Fig. 6 shows the effect of different cleaning bath and cold storage temperatures on power consumption and COP. It can be seen that a low bath temperature of 50° C and a high cold tank temperature of 12.9° C results in the best performance ($COP = 2.93$) for the heat pump. Vice versa the COP drops to 2.6 for a bath temperature of 55° C and a cold tank temperature of 11.7° C.

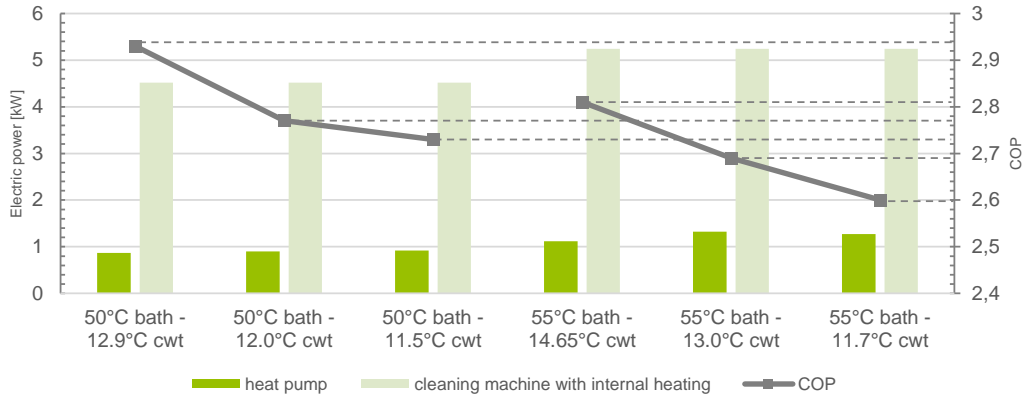


Fig. 6. Performance rating of the heat pump depending on the target temperature of the cleaning machine and the temperature in the cold water tank (cwt) measured with the high stress program

The evaluation of the total efficiency of the crosslinked system it is expedient to interpret the using of waste heat as productive cooling of the machine tool. In the case of 50 °C bath temperature and 12.9 °C cold water tank the usable thermal power (4.5 kW heating and 3.65 kW cooling) results in a total system-COP of 9.39.

5.3. Evaluation of the power-consumption saving in a realistic production scenario

In comparison to the high stress program, a realistic cleaning program consists of a longer spraying period and a much shorter suctioning period. This results in a reduced heating demand with respect to the total energy consumption.

The cleaning bath temperature was set to 60° C, which required a minimum hot-tank temperature of 66° C to ensure stable operation. Due to the use of the heat pump instead of the internal heating system, the electrical power consumption for heating is reduced from 2.05 kW to 1.18 kW for a COP of 1.74. The standard system without crosslinking has a mean electrical power consumption of 10.6 kW. However, the crosslinked system by using a heat pump for reutilization waste heat needs only 8.91 kW.

The overall reduction of energy consumption for the cleaning machine with a bath temperature of 60° C was 18.2 %. This results in an overall reduction of energy consumption of 16 % and a reduction of 43 % regarding the thermal energy. The electric energy consumption for the coupled and decoupled system is shown in Fig. 7.

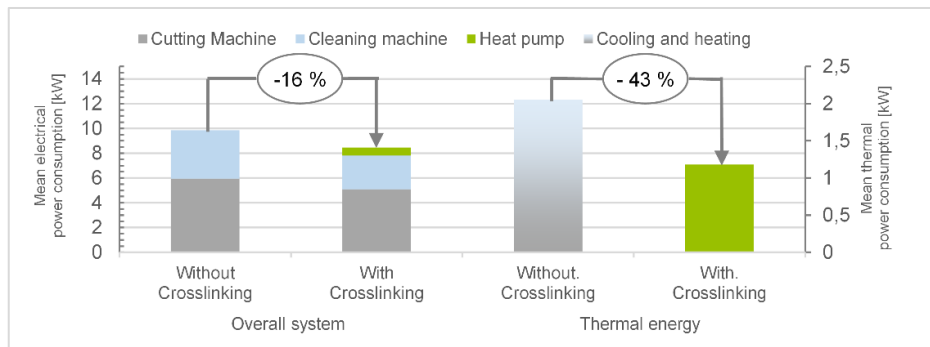


Fig. 7. Overall power-consumption and savings of the crosslinked system by cooling and heating with the heat pump

5.4. Controlling and energy monitoring system

In the course of *Industrie 4.0* the ETA production facility uses an on-line monitoring system for the thermal crosslink system. An ethernet connection of the data server enables remote access to the controlling and from all PC stations, smart phones and tablets within the facility. This system allows both monitoring and controlling of the main parameters. It shows current temperatures of the thermal storages, cleaning and machine bath as well as fluid temperatures in the pipes. Furthermore, COP, EER (energy efficiency ratio), electric consumption, heat

transfer and volume flow rates are displayed. Both, the cleaning and the cutting machine can be shown with more details if necessary. The supervisor can set temperature limits for both thermal storages and the bath of the cleaning machine. The heat pump can be either run in cold or heat guided mode. In heat guided mode, the heat pump keeps the hot thermal storage in its pre-defined temperature range. In cold mode, the cold thermal storage temperature is the reference variable. The graphic user interface enables also non-expert users to perceive all vital system informations and detect any unwanted behavior. While the monitoring system is access-free within the facility, settings can only be changed via a password-protected access.

5.5. Discussion

The storage concept can only mitigate the discrepancy between waste heat and heat demand in certain limits depending on the power of the heat pump. As discussed in section 5.4, there are two control strategies for the system: hot and cold guided mode. If the system is run in hot guided mode and the waste heat is not sufficient the cold storage temperature will gradually decrease until its thermal equilibrium is reached. If that stage is reached, the hot tank temperature will also fall due to the lack of thermal input. In the cold guided mode, the cold storage temperature is set to a certain value. This means that in case of insufficient waste heat, the target temperature of the hot tank cannot be reached.

This can reduce the COP. The efficiency of the heat pump decreases with increasing temperature difference between hot and cold tank. Therefore, the dimensioning of the system should consider the amount of excess heat, heat demand and the power of the heat pump.

6. Conclusion

In this work, the thermal crosslink between a cutting-machine tool and an aqueous-cleaning machine for an increase of the energy efficiency by waste heat reutilization with a heat pump is presented. Three individual subjects with their specific energetic characteristics in crosslinked systems were examined:

- Parts-cleaning machine as a process-heat sink
- Cutting-machine tool as a waste-heat source
- Water/water-heat pump as a heat-transfer technology

It was shown, that state-of-the-art heat-pump technology can increase energy efficiency in production systems. Depending on specific production processes and used machines energy saving up to 43 % are achievable regarding to thermal energy in the investigated study.

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