Monitoring of energy flows and optimization of energy efficiency in a production facility

I. Leobner, K. Ponweiser, C. Dorn and F. Bleicher

***Abstract*—**The present paper reports the findings of an assessment of the energy flows of a building equipped with machine tools and discusses options to optimize its energy efficiency. The energy flows in the buildings are recorded based on collected data and measurement results. Energy efficiency optimization recommendations that are feasible in the existing building structure are discussed. The optimization strategies are evaluated with regard to their energy saving potential by using a building simulation carried out in TRNSYS.

***Keywords*—**building simulation, energy consumption, energy efficiency in production, energy flow analysis,

I. Introduction

Energy consumption in the production industry contributes a large part to societies total energy demand. In industrialized countries it accounts for around 40% of the total energy consumption [1], [2]. Reference [2] estimates the potential for reduction of this energy consumption between 35% and 60% depending on the industry sector. However, according to [3] only a fraction of manufacturing companies actively enforce the implementation of energy-efficient technologies in their production plants, although numerous studies outlining the path to a more efficient production process have been conducted, such as [1], [4] and [5].

One possible approach to reduce the production industry's energy consumption is to increase the efficiency of the production processes themselves. Various studies on different kinds of production processes have been carried out and show significant potential, such as [6], [7] and [8]. Another important sphere of activity identified by [4] is the efficient operation of the infrastructural facilities of production plants. Although the operation of infrastructural facilities consumes a lot of energy, little attention has been paid to this aspect.

The present paper exhibits the results of an assessment and of monitoring a laboratory for production engineering in order to determine the energy flows within the building. On the basis of these results some options of actions and possible directions of further investigation will be discussed.

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II. Methodology

A. Assessment of the laboratory

At the beginning an analysis of the object in its current structural and energetic state was carried out. Therefore all available data of the existing building were collected, with special focus on:

- Building structure and building services
  - General data about the building e.g. location, size
  - Wall construction, windows
  - Ventilation devices
  - Heating systems
- Employees, machine tools and equipment
- Thermal energy demand
- Electric energy demand

B. Measurements

In the next step unavailable data were determined by measurement. Furthermore current measurements were made at the building entrance line to identify the power consumption over time. The energy consumption of the equipment such as computers, kitchen devices, etc. was estimated according to literature and experience. Difficult to determine equipment was measured as well.

C. Energy flows and optimization strategies

Based on the collected data, the results of the measurements, the details concerning the user behavior provided by the staff and the information from the literature the energy flows in the building were determined. They served as a basis for the formulation of optimization recommendations.

D. Simulation

Based on the energy flows determined previously the building was modeled and simulated in the building simulation environment TRNSYS. At first the present state of the building was modeled as verification. Afterwards the formulated optimization strategies were incorporated into the simulation in order to locate the biggest energy saving potentials. Special attention was paid to the specification and the influence of the waste heat of the machine tools.

III. Results of Assessment and Measurements

Table 1 provides an overview of the most significant areas of the gathered information to give an impression of the laboratory's size and characteristics.

TABLE 1
KEY DATA OF BUILDING

Location	Vienna (48°11´16 N; 16°23´51 E)
Building area	1077.48 m²
Building height	3.7 – 6.9 m
Heat transfer coefficient walls	0.25 W/(m²K)
Heat transfer coefficient windows	2.85 W/(m²K)
Ventilation system	Only in server room
Heating system	Oil fired
Water heating	Electrical
Employees/Interns	24/3
Equipment	1 computer per person Usual office equipment 1 fully equipped kitchen 1 compressor
Machine tools	31 of varying characteristics
Thermal energy consumption (4 year average)	130.1 MWh/a
Electric energy consumption	No data available

Since there was no data available about the electric energy current measurements were made at the building's electrical main supply in order to determine the consumption of electric energy.

21 complete days were measured over a time period of two month gathering an average value ever 30 seconds.

One of the most eye-catching characteristics of the current measurement was the chopping alteration of the consumed effective power even at nighttime when there was no activity at all. (See fig. 1)

An interpretation could be the continuous activities of the compressor, which maintains a certain pressure in the leaking pressurized air distribution system. Summarized over a year 27 MWh of electrical energy are wasted this way. This phenomenon seems to be a common problem in production plants as F. Alhourani states in [1].

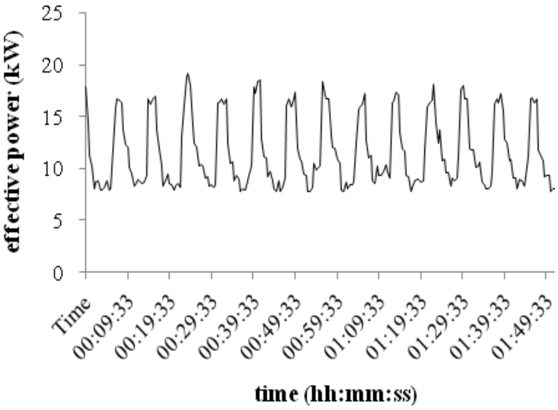

Fig. 1: Activity of compressor during night-time

Another critical fact was that even on days when no activity was observed at all, we measured a basic load of about 300 kWh per day, whereas on days of high activity the consumption would not exceed 550 kWh per day. That means the basic load accounts for almost two thirds of the total energy consumption. Fig. 2 shows the obtained electric power on a Sunday. The basic load varies between 8 and 10 kW, not including the compressor. It can also clearly be seen that someone was working a few hours in the afternoon.

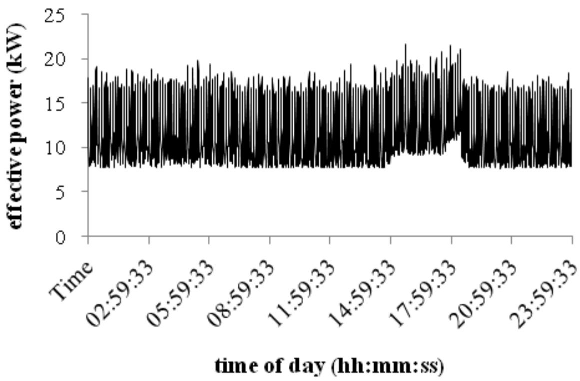

Fig. 2: Obtained effective power on a Sunday

Another fact that made it difficult to give a profound estimation of the yearly energy consumption was the differing daily consumptions. Fig. 3 shows the obtained effective power of three sequent labor days. On day two the consumption was 523 kWh but on day three the energy consumption could not even reach a value 400 kWh.

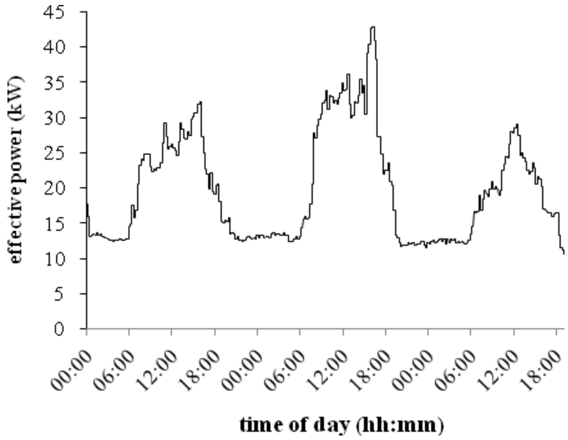

Fig. 3: Obtained effective power over a period of 3 days (averaged over 15 minutes)

To achieve an accurate approximation of the electric energy consumption we identified three characteristic profiles: work day with high activity, work day with low activity and holiday. Out of these profiles we created a profile for a typical year and thus calculated an electric energy consumption of 147 MWh per year.

Regarding this key data stated above the laboratory could be comparable to a small-scale enterprise with a flexible single piece or small batch production.

Another finding pointing at a possible conservation of energy, was the fact that the employees reported frequent overheating, including during the winter month. This correlates to a high heating energy demand of 120.7 kWh/(m²a). This was due to the fact that the heating system control was based on the outside temperature and did not take into account the waste heat of the machine tools distributed inside the building.

IV. Energy Flows

Based on the measurements and the assumptions made, the energy flows shown in fig. 4 arise. For the energy consumptions of office equipment, lights, safety installations, central IT-systems, etc. reference values according to [9] were used for calculation.

V. Simulation and Optimization

To assess the usefulness of optimization measures, the building was first simulated in the existing condition. The parameters of the simulation were selected in order that the simulation results showed consistency with the results of the measurements.

To specify the waste heat emitted by the machine tools a balance was drawn around the system "machine tool" (see fig. 5).

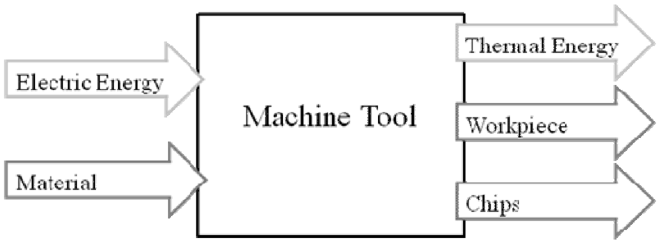

Fig. 5: Energy and mass balance around machine tool

The entering electric energy can leave the machine only as thermal energy or stored in the workpiece and chips. This stored energy consists of the energy spent generating a new surface and the deformation of the chips. Calculations according to [10] showed that these parts of the energy are only a small fraction of the thermal energy leaving the balance. Therefore we assumed that all the electric energy consumed by the machine tools is converted into heat, which again is distributed into the room. Unfortunately the waste heat of the machine tools is at a very low temperature level and the machines have internal cooling circuits, which makes the use of the waste heat in a thermal system impossible.

Table 2 gives an overview of the characteristics of the simulation carried out in TRNSYS.

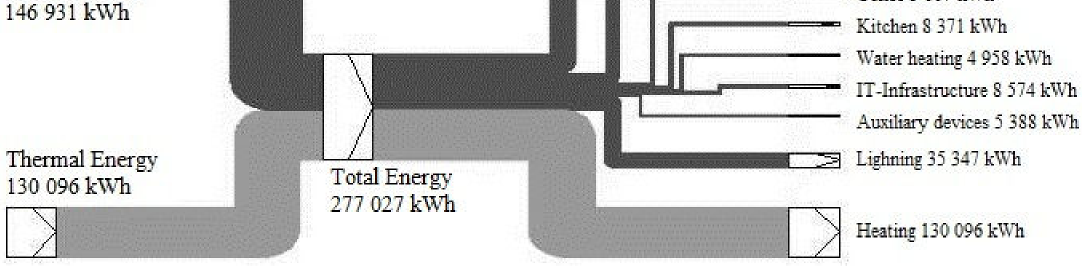

Fig. 4: Energy Flows in the Building, present status

TABLE 2
KEY DATA OF SIMULATION

Simulation tool	TRNSYS 16
Simulation time	9000 hours (1 year, 10 days)
Simulation time step	1 minute
Thermal zones	8
Monitored variables	Temperature in thermal zones Sensible heating demand Electricity demand Control signals
Modeled components	Building Behavior of users Weather and shading Waste heat of machine tools Electricity Consumption Heating System

The simulation is in close agreement with the actual measured data. The heating demand was calculated at 133.2 MWh per year, whereas the collected data suggested 130.1 MWh per year.

In the next step optimization measures were implemented in the simulation. At first 8 cm of further isolation was applied to the outside walls and ceiling and the heating control strategy was changed from outside temperature controlled to room temperature controlled. This lead to a reduction of the thermal energy demand for heating from 120.7 kWh/(m²a) to 75.7 kWh/(m²a) according to the simulation. Along with that, the thermal comfort in the building was enhanced because the new control strategy prevented frequent overheating.

Furthermore, photovoltaic cells and a solar collector for water heating were installed on the roof. The implementation of advanced technologies to cover the energy demand, such as geothermal energy or large thermal storage devices was not possible due to environmental restrictions. Table 3 and 4 summarize the most important technical data of the installed systems.

TABLE 3
TECHNICAL DATA OF PHOTOVOLTAIC

Azimuth angle	30°
Zenith angle	60°
Size of module	1 m²
Number of modules	372
Total power installed	37.31 kWp
Maximum power point	17V/5.9A
Maximum power point tracker	Yes

TABLE 4
TECHNICAL DATA OF SOLAR COLLECTOR

Azimuth angle	30°
Zenith angle	60°
Size of collector	15 m²
Efficiency	0.8
Desired water temperature	60°C
Daily water demand	175 Liters
Size of collector	15 m²

According to the simulation the photovoltaic cells produced 37.6 MWh of electric energy during the year of which 34 MWh were consumed by the facility itself and 3,7 MWh were supplied into the grid. The solar collector produced 2.9 MWh of thermal energy during the year and reached a solar fraction of 81.3% when combined with a heat storage boiler of 1 m³ (largest possible due to room geometry).

According to the simulation 46.4 MWh or 16.7% of the total energy consumption could be saved by reducing the heating demand through improved control strategies. 37.4 MWh or 13.5% of the energy demand drawn from the grid

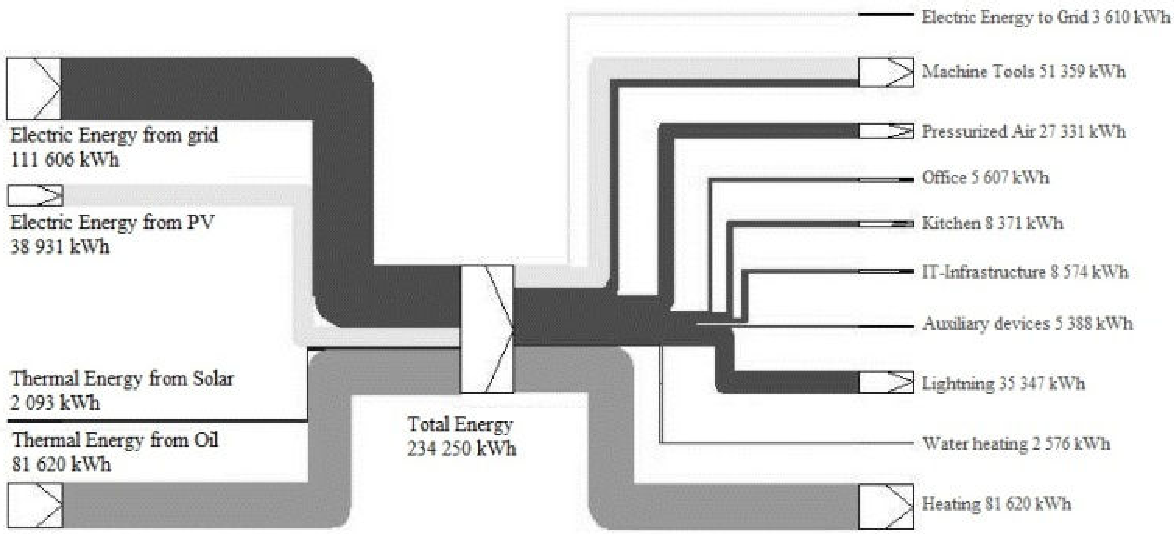

Fig. 6: Energy Flows in the Building, after optimization

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could be substituted by solar energy converted in photovoltaic and solar collectors installed on the building (service water was heated electrically).

Based on these results Fig. 6 shows the energy flows calculated by the simulation after the implementation of all the suggested optimization strategies. It shows a reduced thermal energy consumption from oil and electric energy sources due to the energy savings and the substitution by photovoltaic cells and solar collectors on the input side. On the demand side the heating is reduced, but still powered by oil. The service water is now mainly heated by the solar collectors and only requires very little further electrical heating. The electricity demand remains mostly the same as before; only the most of machine tool's demand can be covered by the energy from the photovoltaic system. Furthermore, there is some electricity supplied into the grid.

VI. Conclusion

Previous research has shown different ways to optimize production processes in terms of energy efficiency, but as stated in the introduction process optimization is only one field of action that needs to be incorporated into a holistic approach towards sustainable production. In this study we specified the energy flows of the whole facility in order to achieve a more extensive image of the system. Based on these findings we were able to give a few simple recommendations to reduce the energy demand significantly without making any changes to the processes themselves.

This paper offers one point of view on the task of energy optimization of production plants. Coupling e.g. assessment of the energy flows in the system, process improvement, sustainable product design, etc. could be very promising to take advantage of more of the energy saving potential. For instance the temperature level of the waste heat of the machine tools is quite low and it is distributed freely into the room. Therefore it is not eligible for use in thermal systems. If the temperature level could be raised in the process, the waste heat could be gathered and used for other applications, such as service water heating.

Of course the efficiency discussion can not only be lead from the technical point of view. To achieve a strong impact economic incentives and appropriate steering tools will be required. There have been extensive investigations on key values and evaluation systems concerning parts of the system such as [11] or [12] but there is still need for further research on this topic.

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