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A holistic approach to energy efficiency assessment in plastic processing

B. Alexander Schlüter [a, *], Michele B. Rosano [b]

[a] Department Production and Energy, IdE Institute decentralised Energy Technologies gGmbH, Ständeplatz 15, 34117, Kassel, Germany
[b] Sustainable Engineering Group, Curtin University, Perth, Australia

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ABSTRACT

Significant increases in industry energy efficiency are crucial for the transformation of the world's energy systems. Many production sites offer high energy savings capabilities, and if these are accompanied by short periods of economic amortization, companies should be willing to act. This case study provides a novel and extended energy assessment for plastics processing plants including primary energy, greenhouse gas emissions, and energy costs. The research distinguishes between the standard form of separate individual energy assessments and provides a more innovative holistic approach taking all relevant energy flows within the production system into account. Dynamic simulation offers a quick and effective way to predict the results of the possible energy saving measures highlighted in this analysis. The paper presents validated energy consumption simulations based on realistic processing conditions for two injection molding factories in different climatic zones. The results show that combining a number of separate energy saving measures can reduce the primary energy demand by around 26% for a German plant under temperate climate conditions and 20% for a Western Australian plant under Mediterranean conditions. However, when the separate energy saving measures are holistically combined the reduction in energy use significantly increases to 41% and 43% respectively. This holistic energy strategy involves incorporating better cogeneration and waste heat recovery options. For small and medium sized companies in particular major energy infrastructure investments may often be considered too expensive without examining the extended benefits from a holistic energy assessment perspective. In contrast, a holistic framework, like the one suggested in this paper could provide a number of new options for increasing energy efficiency that individually might normally not be accepted under conventional economic rate of return analysis.

1. Introduction

The goal of this paper is to show the potential savings in primary energy use, carbon emissions, and energy costs in utilizing a holistic framework for energy savings in plastic processing in different climatic zones (Germany and Australia). In addition, it is interesting whether a holistic approach for assessing efficiency measures is more promising than a separate energy efficiency assessment. According to the ISO 14044, the life cycle assessment (LCA) is a method to evaluate the environmental impact of a product running through a certain system for a given combination of inputs (ISO, 2010). An energy efficiency analysis on the other side focuses on the energetic demand of a technology or process. A reasonable procedure is published by VDI (1998) and includes the main steps acquisition of the actual state, proposals for increasing the energy efficiency, development of a whole concept, assessment of the proposals—which can also include the calculation of the cost efficiency—and realization as well as success monitoring. A holistic approach goes one step beyond and reveals the impact on the energy efficiency of the whole system when changing one part of it (VDI, 1998).

In this current paper, the importance of the research subject is determined through a literature review and the use of case study analysis. Two different examples of holistic energy efficiency assessment changes in plastics processing are examined and evaluated. Particular attention is paid to energy demand. Plastics processing industry case studies are used as examples of the potential

* Corresponding author. Current address: basINGa Ingenieurbüro B. A. Schlüter, Percevalstr. 27, 23564 Lübeck, Germany.
E-mail address: B.A.Schlueter@outlook.de (B.A. Schlüter).

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for energy efficiency improvement using a more holistic energy efficiency assessment framework in manufacturing and production applications.

1.1. Standard and innovative ways of assessing energy efficiency

Energy efficiency literature contains a lot of articles from authors who focus on a single production technology or on the improvement of a singular processing efficiency. Wu and Wang (2014) for example conducted an energy and exergy analysis of a combined heating and power system with a heat pump. The paper showed under which circumstances the exergetic losses can be considerably reduced.

Lythcke-Jørgensen *et al.* (2014) described the integration of second generation bioethanol production together with combined heat and power units. The authors highlighted the benefit of heat recovery in a heat integration network which significantly increased the exergy efficiency of the overall integrated system.

Whilst Input-Output analysis, based on the First Law (conservation of mass and energy) and Second Law (degradation of energy quality) of thermodynamics have been popular in providing an exergy analysis of inefficiencies in industrial processes (Szargut *et al.*, 1988; Ukidwe *et al.*, 2009), these methods neither capture the environmental (greenhouse gas) impacts of energy consumption nor the potential for internal energy efficiency improvements. This is where a “holistic energy assessment” could be valuable.

Ukidwe *et al.* (2009) stated that the use of the first law of thermodynamics is indispensable for the design and operation of every industrial process. The paper examines the potential for including both heat losses and energy production efficiency within the overall economic and environmental impacts of energy efficiency assessment, beyond just single point or total energy use or carbon footprints. Such a hybrid analysis could provide a smarter and more effective energy efficiency assessment framework.

Some papers have recognized the potential of the total system, holistic assessment of energy use as an alternative method for reviewing energy efficiency across both production and industry applications.

Okeil (2010) applied a holistic approach in comparing building energy efficiency. In this sector, incoming solar radiation has to be considered appropriately. He concluded that more energy efficient forms of buildings can be discovered using the holistic approach when compared to the results achieved conventionally with single source energy assessments. Similarly, O'Donnell *et al.* (2013) considered the coupling of building functions with other important energy aspects necessary for building managers in their determination of energy efficiency outcomes and design guidelines.

Munir *et al.* (2012) provided a holistic carbon planning approach for industrial parks. Several scenarios were compared with the help of pinch analysis and network allocation diagrams in order to find minimum CO_2 targets for the refineries in the industrial area.

Kimming *et al.* (2015) presented how an organic dairy farm can become self-sufficient in energy supply. The farm is able to decrease the production emissions of 1 kg of energy-corrected milk between 32 and 46 % by utilizing a total energy system holistic approach like that described in this paper. The authors also included the use of renewable energy in improving overall energy efficiency.

Similarly, Sproedt *et al.* (2015) recognized the complex interrelations between the environmental and economic performance dimensions in production systems and also highlighted the need for a whole energy system analysis approach in guiding decision makers and in identifying possible energy efficiency measures.

As depicted above, literature highlights the potential in supporting the holistic approach that includes many additional advantages when compared to separate source energy assessments. Schlüter (2013) compared both single source and holistic energy assessment methods to determine the benefits and justify the additional effort required when assessing energy use and efficiency more holistically. In this paper, the research is not only presented to an English speaking community but has also clearly been developed further so that now an entire plastics factory is undergoing a holistic energy assessment in plastics processing manufacturing including energy supply, building services infrastructure, and the process machinery. Furthermore, the economic impact is considered to help validate the associated benefits of the holistic energy assessment framework.

1.2. Energy demand in plastics production and processing

In 2012, the world's polymer production was 299 Mtons making plastics processing an important field of employment in many European countries (PlasticsEurope, 2015). Plastics processing is also energy intensive. Rubber and plastic production is 3.1% of the total energy demand of German industry (Umweltbundesamt, 2012). Schlüter (2013) presented an example of a German factory in which only about 4% of the primary energy goes to the core process—the heating and melting of the granulated polymer inside the extruders—with 21% for machining power (exclusive of the core process) and 12% for processing infrastructure including pneumatic systems, chilling machines, coolers, heaters, computers, and pumps. Electricity losses are some 63% of total demand. The company receives its electric energy from centralized supply (grid). As a result the grid's primary energy factor—the ratio between primary energy input and the end energy output—is quite high leading to a very low degree of primary energy efficiency for the overall plastics processing.

The intense usage of electric energy results in considerable energy costs and greenhouse gas emissions. In many countries energy consumption makes up a large proportion of the overall costs of plastic processing and production, between 5 and 10% in Germany alone (Bürkle *et al.*, 2007). Given this fact and the upward trend of energy prices, decision makers are increasingly seeking to reduce energy costs and introduce both energy efficiency assessments1 and energy efficiency measures (Brown and Yücel, 2002).

Fig. 1 illustrates the points with high energy demand in an exemplary German plastics processing plant. The factory processes non-hygroscopic polymer only and therefore does not have to dry the finished product.

Fig. 1 highlights that more than half of the primary energy is needed by the processing machines (excluding heating of the cylinders).

1.3. Examples of separate energy efficiency measures in plastic processing areas

Detzer (1995) noted that in the case of production areas involving high internal thermal loads, such as those caused by the use of multiple hot machines, an implementation of layer ventilation instead of mixed ventilation offers many benefits. Firstly, it saves energy because it supplies fresh air where it is actually needed—from the ground to two meter height—instead of servicing the complete height of the hall. This then reduces the HVAC-system's electric demand for fans and chilling machines because of the resulting smaller necessary volume flow of fresh air. It also improves the comfort and work conditions of the employees which may lead to less demand for sick leave, increased concentration, and, accordingly, higher productivity (Schäfer *et al.*, 2013).

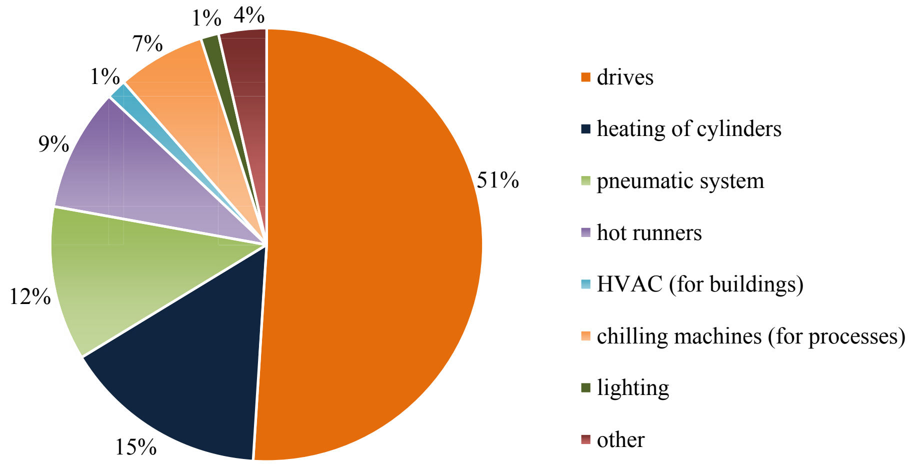

Fig. 1. The division of primary energy demand in a typical German injection molding factory.

The particular injection molding technology chosen for the plastic processing—hydraulic (electro-hydraulic), fully electric (electro-mechanical), and hybrid (parts of both)—can also influence overall energy efficiency (Madan *et al.*, 2013). Today, most companies still use the more inefficient hydraulic technology because it has an average life span of 15–20 years. Whilst electric machines are noticeably more expensive, they also have considerable benefits: They are more energy efficient and can process plastic faster. A hybrid drive is often considered by industry to be a reasonable compromise between energy efficiency, short cycle times, and cost effectiveness. There have also been other technological improvements like multicomponent injection molding and computer aided optimization of production processes.

In addition, plastics processing factories often use compressed air for handling, packaging, and transport. Pneumatic systems are very inefficient in terms of their energy consumption due to major losses from the compression of the air to its final distribution. Saidur *et al.* (2010) noted this in their research with losses from 81 to 90% of final (electric) energy use. Decreasing the operation pressure or optimizing the distribution network can reduce the electric energy demand of pneumatic systems (Radgen and Blaustein, 2001). However, substituting the pneumatic system with electro-mechanical devices can be a double edged sword. On the one hand, the degree of energy efficiency increases substantially. On the other hand, the potential for waste heat recovery is lost. A holistic energy assessment should therefore consider the ramifications of different technologies operating in tandem so as to ensure enhanced overall collective energy efficiency.

2. Modeling, validation, and verification

The simulation (see Section 3) in this paper is based on different factories: Firstly, two real life injection molding plants in Kassel, Germany and in Perth, Western Australia are assessed. Measured data includes temperatures, energy demands, and volume flows as well as information on operation time. This data was collected from the factories and/or from a laboratory at the University of Kassel.

In the study presented by Schlüter (2013) the heating system of the building, the waste heat from the air compressor, the cooling system, and the heating demand of the barrels are combined in a thermal-linked system. In this paper the air conditioning and ventilation is conducted with open windows and three fans. It is common for plastic processing factories in temperate climates not to use chilling machines for this purpose leading to temperatures of up to 40 °C in the production hall on warm and sunny days.

The whole simulation model consists of the following sub-models of operation:

- Injection molding machines,
- Heating systems for extruder and facilities,
- Thermal energy storage,
- Combined heat and power plant,
- Chilling machines, coolers, and fans for ventilation,
- Pipes and heat exchangers,
- Pneumatic system,
- Lighting.

The following section provides a brief introduction to important sub-models within the simulation model.

2.1. Injection molding machine and thermal energy storage

The modeling of the machines and the energy storage is based on the further published node model (Schlüter *et al.*, 2011, 2012). It simplifies the body to be simulated by sliding it into several layers and lets thermal energy flow between those layers. This procedure enables the solving of simple differential equations for the time and position depending states. This is easier than solving a partial differential equation. The heating up-phase of the machines is particularly important. The temperature of the drive and the mold substantially influence the thermal energy flows of the cooling system(s). The validity of the sub-model is proven with the help of several data sets from real injection machines.

For the thermal energy storage, Fig. 2 gives two examples for the comparison of measured and simulated temperatures of water flows inside two 500 l storage tanks. In both cases water, warmer than the storage water, is used.

The four graphs show that before increasing in two phases, the water filled storage temperature remains constant. The results are fairly similar to the data obtained from measurement. In this paper, the root mean square error (appr. RMSE) e_{RMSE} in Eq. (1) is used to compare measured data y_{meas} and simulated data y_{sim}, both with an amount of n.

$$e_{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[y_{meas}(i) - y_{sim}(i)]} \quad (1)$$

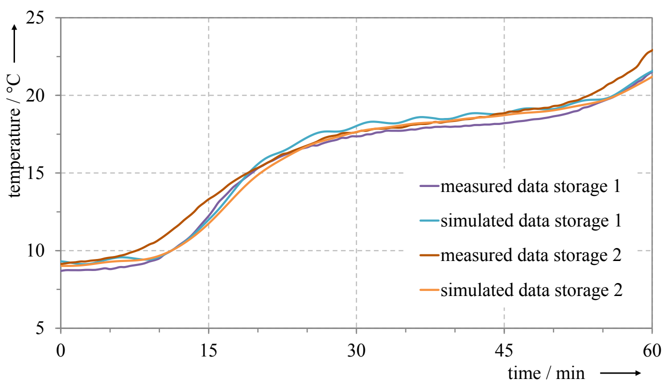

Fig. 2. Validation of the storage model: The core temperatures of two water storages are measured and simulated, modified from Schlüter (2013).

On the basis of the 500 l (see above) and a 300 l storage, the RMSE of this sub-model is approximately 0.5 K.

2.2. The heating system

As explained above, the core process of the factory is the heating and melting of plastic inside the extruder cylinders. Given the fact that the internal heat from the screw is not sufficient for most injection molding machines, external heating is necessary. Electrical heating barrels are currently the state of the art heating mechanism for this. Due to the electrical primary energy inefficiency of the heating barrels, research continues to be done on developing solutions with alternative energy sources including the combustion of natural gas and thermal oil systems (see Schlüter and Hesselbach, 2010; Schlüter *et al.*, 2012).

With regard to the model, the thermal oil system is responsible for the heat needed by the extruder. The natural gas provides thermal energy and the energy for the oil system's losses. Eq. (2) gives the power balance of the combustion system.

$$\dot{m}_{fuel}h_{fuel} + \dot{m}_{air}h_{air} = \dot{Q}_{oil} + \dot{Q}_{H_2O} + \dot{Q}_{loss} + \dot{m}_{fg}h_{fg} \quad (2)$$

$\dot{m}_{fuel}$ is the mass flow of the fuel and h_{fuel} its specific enthalpy while $\dot{m}_{air}$ is the mass flow of the inlet air and h_{air} its specific enthalpy. On the right side of the equation are the energy flows $\dot{Q}$ of the oil, water (short: H_2O) and of diverse losses next to the energy flow contained in the exiting hot flue gas (fg).

In the next step, the factor of efficiency of the heat transfer from flue gas to thermal oil η_{fg-oil} inside the heat exchanger is considered (Eq. (3)).

$$\eta_{fg-oil} = \left(\dot{V}_{oil}\,\rho_{oil}(\vartheta)c_{p,\,oil}(\vartheta)\Delta\vartheta_{infeed-return,\,oil}\right)\Big/\left(\dot{V}_{ng}\,\rho_{ng}\,H_u\right) \quad (3)$$

The volume flows of the combustion gas $\dot{V}_{ng}$ and of the oil $\dot{V}_{oil}$ as well as oil temperatures ϑ at various sections are measured while the density ρ_{ng}, the heating value H_u of the natural gas as well as the density $\rho_{oil}(\vartheta)$ and the specific heat capacity $c_{p,oil}(\vartheta)$ are provided by the supplier. Validation of the heating sub-model is possible based on the calculated efficiency factor obtained from the measurements. Assuming that the specific heat capacity is constant, the factor of efficiency can also be calculated with Eq. (4) (Schlüter, 2013).

$$\eta_{fg-oil} = \eta_{he}\cdot\left(\vartheta_{fg,0} - \left(\vartheta_{oil,\,in} + \Delta\vartheta_{oil,\,in-fg,\,out}\right)\right)\Big/\left(\vartheta_{fg,0} - \vartheta_b\right) \quad (4)$$

As the burner has losses at the surface, a degree of efficiency of the heat exchanger η_{he} for the theoretical calculation is needed. It can be calculated after having obtained η_{fg-oil} from Eq. (3). ϑ_b is the input temperature of the inlet air (in most cases the ambient air temperature) while $\vartheta_{fg,0}$ is the temperature of the flue gas at its origin and hottest point: the combustion. Next to $\vartheta_{fg,0}$ and η_{he}, the numerator contains the inlet-temperature of the oil $\vartheta_{oil,in}$ and the temperature difference between oil-inlet and outlet of the flue gas $\vartheta_{oil,in} + \Delta\vartheta_{oil,in-fg,out}$.Fig. 3 shows the comparison of the simulation's result and of the data measured.

The factor η_{he} is constant over the temperature range depicted. This is positive for the simulation and in validating the model.

2.3. Pipes and hoses

Pipes and hoses are necessary to transport heat and cold within the processing system. Even when they are insulated, however, they emit thermal energy to the environment. For the modeling, it is assumed that the pipes and hoses have the form of a cylinder and hang loose above the ground. They therefore have no contact with other bodies, which would allow an exchange of thermal energy; VDI (2010).

The loss of heat and cold $\dot{Q}_{loss}$ is calculated with Eq. (5) (Schlüter, 2013).

$$\dot{Q}_{loss} = (UA)_{pipe}\cdot f_{corr}\cdot\,\Delta\vartheta_m \quad (5)$$

with $\Delta\vartheta_m = (\Delta\vartheta_a - \Delta\vartheta_b)/\ln(\Delta\vartheta_a/\Delta\vartheta_b)$.

U is the combined heat transfer of the pipe or hose while *A* stands for its outside surface area. The logarithmic temperature difference $\Delta\vartheta_m$ given below Eq. (4) is known from VDI (2010).

Since convection and radiation are not proportional to the rising temperatures of the pipes the factor f_{corr} is necessary. It is given by a characteristic curve depending on the temperature gradient between the pipe's inside and the environment's temperature (brochure of Logstor A/S, Løgstør, 2011).

Four different water temperatures (10, 65, 75, and 85 °C) were taken for the validation of this sub-model. The RMSE regarding all these tests is 0.2 K and is therefore approximately as high as the measuring uncertainty of the temperature sensors.

2.4. Coolers

Coolers are necessary for bringing away heat from processing machinery. The model factories use dry coolers. DIN 18599-7 (2007) offers a way to model the heat transfer by Eq. (6).

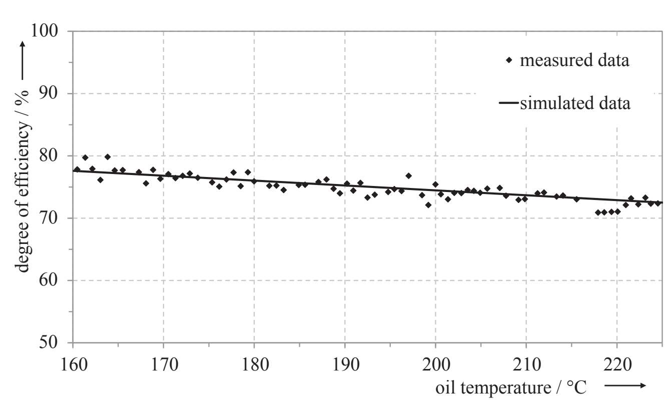

Fig. 3. The measured and the simulated degree of efficiency of a heater decreases with increasing oil temperature, $\eta_{he} = 92.5\%$, $\vartheta_{fg,0} = 1200$ °C, $\vartheta_b = 20$ °C, modified from Schlüter (2013).

$$\vartheta_{fluid,\,out} = \vartheta_{fluid,\,in} - \eta_{dc} \cdot \left(\vartheta_{fluid,\,in} - \vartheta_{amb}\right) \tag{6}$$

At first, the specific factor of the cooler η_{dc} has to be calculated on the basis of given temperatures for the cooler. Given the ambient (ϑ_{amb}) and fluid's inlet temperature $\vartheta_{fluid,\,in}$, the outlet temperature $\vartheta_{fluid,\,out}$ can be simulated. The cooler's electric demand is taken from the manufacturer's data and cross checked with measurements. In reality, most coolers work with in-line units that are operated separately. Therefore, the model includes a connection in series. Fig. 4 depicts the response of the cooler-model for different inlet-temperatures of the fluid (Schlüter, 2013).

In the case of rising ambient temperature and constant inlet of liquid, the outlet temperature goes up as well. As long as no extreme values for humidity and temperatures are chosen, the model provides coherent results for simulating real dry coolers.

2.5. Combined heat and power plant

A combined heat and power plant (CHP) makes heat and electric energy usable due to decentralized cogeneration. The temperature of the thermal energy flow is high enough for lithium bromide-based absorption chilling machines (ACM), at about 85 °C. The leading factor of this sub-model is the necessary heat flow for the ACM. The generated electric power in the n running hours during the year is considered in the economic and ecologic records. The degrees of efficiency of the electric and thermal energy flows (η_{el}, η_{th}) are non-constant. While the thermal one decreases with increasing point of operation, the electric one increases. The sub-model contains these relations, see Eq. (7) (Schlüter, 2013).

$$\eta_{sum} = \eta_{th} + \eta_{el,\,p\,100\,\%} \cdot \left[1 - e^{-p\left(\tau + p/f\right)}\right] \tag{7}$$

The working point of the plant can have a value between 0 and 100%. The factors τ and f depend on the characteristic curve of the individual CHP. The resulting curve has a logarithmic shape.

2.6. Chilling machines

The Carnot process provides equations to model the compression (CCM) and the absorption chilling process. The ideal energy efficiency ratio (abbr. EER) ε_{ca} of the compression procedure can be calculated with the help of the evaporation temperature (T_{ev}) and condensation temperature (T_{con}) as shown in Eq. (8).

$$\varepsilon_{ca} = T_{ev}/(T_{con} - T_{ev}) \tag{8}$$

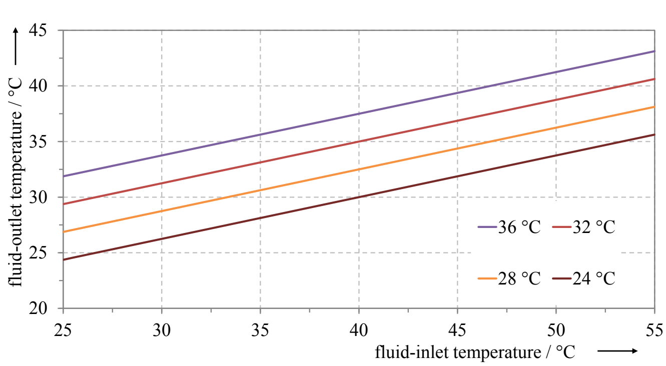

Fig. 4. Validation of the cooler model: The results vary for different ambient temperatures, modified from Schlüter (2013).

An absorption chilling machine includes thermal rather than mechanical compression. Its ideal EER $\zeta_{ACM,\,id}$ in Eq. (9) requires the temperatures of the heating flow (T_h) and of the condensation (T_{con}) as well as the EER of the mechanical compression ε_{ca}.

$$\zeta_{ACM,\,id} = \varepsilon_{ca} \cdot (T_h - T_{con})/T_h \tag{9}$$

In order to determine whether the Carnot equations fit for actual machinery, the exergetic factors of efficiency $\eta_{ex,\,CCM}$ and $\eta_{ex,\,ACM}$ as ratios of measured and ideal EER are used (Eq. (10) and Eq. (11)). An exergetic factor of nearby 1 (=100%) would be a good sign for the usability of a chilling machine model based on Carnot.

$$\eta_{ex,\,CCM} = \varepsilon_{CCM,\,real}/\varepsilon_{ca} \tag{10}$$

and

$$\eta_{ex,\,ACM} = \varepsilon_{acm,\,real}/\zeta_{ACM,\,id} \tag{11}$$

In Fig. 5, the EER of a real chilling plant on the basis of an indirect measurement as well as the calculated EER from Carnot is shown. The exergetic factor of efficiency facilitates the comparison of both measures.

The huge difference between the model and the measurement of the real device is obvious. Since the results for the compression technology also show a large difference, the Carnot equations are not usable for simulating chilling machines. Hence, the following modeling is based on characteristic curves.

For an absorption chilling machine, a compression chilling machine has three important temperatures that influence the EER. The model uses Eq. (12) for calculating the EER (Schlüter, 2013).

$$\varepsilon = \varepsilon_b \cdot \prod_{i=1}^{n} \chi_i(\vartheta_i) \tag{12}$$

The EER ε_b and the functions $\chi(\vartheta)$ depend on published measurement data. n and i are indexes. The example for the ACM (Fig. 6) is based on a heating flow temperature of 86 °C.

The models for both the compression and the absorption technology are validated and verified with additional characteristic curves leading to an uncertainty of maximum 5%.

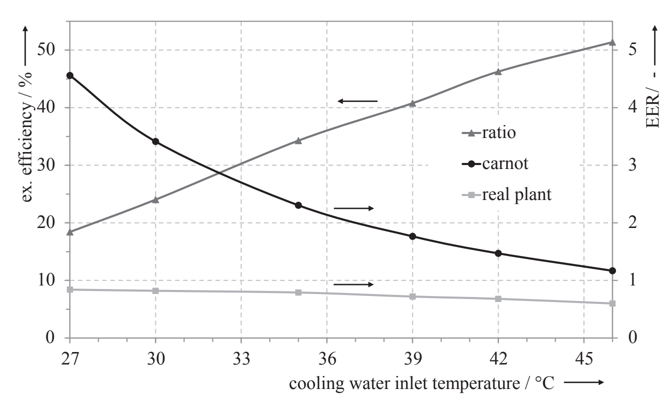

Fig. 5. Efficiency factors of an absorption chilling machine: The difference between the theoretical efficiency factor of a chilling machine based on the equations of Carnot and the measured factor in a real plant drops with cooling water at higher temperatures. The exergetic factor of efficiency is given for clarification, modified from Schlüter (2013).

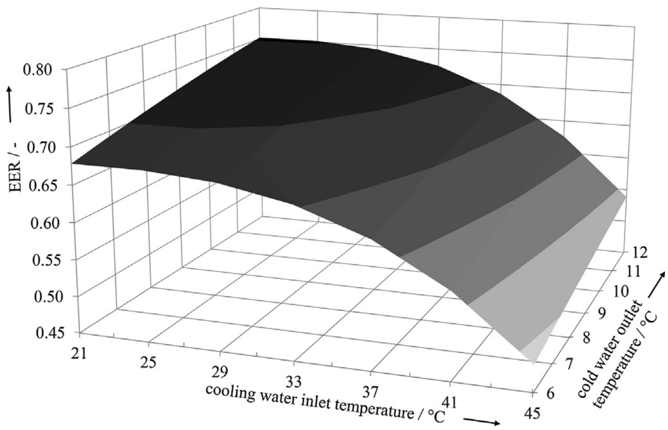

Fig. 6. The simulation of the absorption chilling machine's EER: The result is a three-dimensional field. In this example, the heating temperature is 86 °C, modified from Schlüter (2013).

2.7. Validation and verification of the whole model

After the single models are validated and verified, they are then combined to represent the whole model. Rabe *et al.* (2008) depicts multiple possible techniques for validating the analysis including:

- Change of single parameters,
- Analysis of extreme values,
- Desk checking,
- Analysis of sensitivity, and
- Comparison with other simulations.

Three validations of the whole model were conducted and are presented in the following sub-sections.

2.7.1. Comparison with other simulation models

The first validation involves the comparison of the above model with another simpler model. This approach helps to indicate if the dynamic model can simulate one specific, non-dynamic state. For this purpose, its adjustable screws, e.g. a constant ambient temperature 20 °C, are fixed and another – this time – static model is created. The boundary conditions for both simulations are the same. The period under review is 30 days with non-stop production so that the state in the thermal energy storages should mainly be steady. Table 1 shows the results of both simulations regarding the demand of primary energy, the emission of CO_2-equivalents, and the costs of energy.

Due to the fixed adjustable screws the dynamic model only presents partial matching. Nevertheless, this method assesses a difference of 1.2% in all three fields. Additional comparisons prove that this outcome is not random.

2.7.2. Analysis of extreme values

The second method of validating the combined model is in the analysis of the extreme values. There are numerous possibilities for

Table 1
One way to examine the factory model is to compare its simulation run with fixed adjustable screws and the run of another static model, translated from Schlüter (2013).

	Demand of primary energy in kWh/a	CO_2e emission in t CO_2e/a	Energy costs in €/a
Dynamic model	398,689	86,358	20,150
Static model	394,110	85,364	19,918
Difference in %	1.2	1.2	1.2

Table 2
The denomination in the analysis of extreme scenarios is shown here, translated from Schlüter (2013).

	Pipe length 2 m	Pipe length 20 km
Storage volume 1.76 m^3	a	c
Storage volume 176 m^3	b	d

setting extreme values. Since the volume of thermal energy storage and of the pipes length utilized is important in this analysis, they are chosen to help validate the combined model through extreme value analysis. The volume flow of the medium, the ambient temperature, the coefficients of heat transmission, and the thermal energy input are kept constant. The extreme value analysis is based on four scenarios (Table 2). Scenario a is the only non-extreme case.

Fig. 7 includes the whole model's response for each of the four scenarios.

The comparatively small volume of the storage and the short pipes (Scenario a) leads to a quick increase in temperature but exhibits a slightly decreasing gradient from 0.25 h on. The result of choosing the same storage with long pipes (b) saturates at about 30 °C. In the case of large storage volume, the energy imparted has very little effect on the outlet temperature even after eight hours (Schlüter, 2013), suggesting that the model's responding time rises with increasing volume, like in real storages.

2.7.3. Validation by means of measured data

The third method of validation involves actual comparison with real production data. The cooling demand of a plastics processing factory is suitable for the validation of a major part of the model. During the measurement duration (1000 min), the number of molding machines operating may change given differing machine setup times and stoppages. Boundary conditions like cycle times, shot weight of the polymer, and energy supply are implemented as average values. Two types of measurements are very important for this comparison: the cooling demand and the electric energy input to the machines as the basis for the simulated cold demand of the molds. The analyzed percent difference is between 1.2% and 3.8% and therefore smaller than the measurement uncertainty of the sensors. Hence, the simulated combined results are considered valid and a reliable estimate of actual energy used (Schlüter, 2013).

3. Simulation scenarios and results

In this section, the energy efficiency of two factories in Germany and Western Australia is analyzed with the help of scenarios.

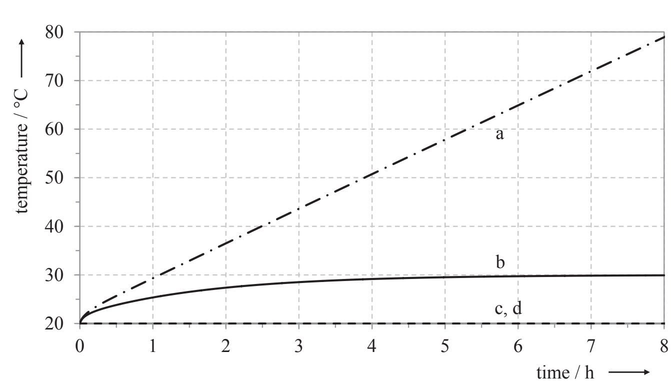

Fig. 7. Analysis of extreme values: Scenario a is based on normal values for the storage and length of the pipes, scenarios b, c, and d are based on at least one extreme value. The runs for c and d are so close lie that they cannot be distinguished, modified from Schlüter (2013).

Previously, the energy use of the case study factories is assessed on the basis of auditing and inspection. The results of the current and historical states provide data for the scenarios "base case" and "simple measures".

Table 3 includes the important parameters for the use of different forms of energy. Germany has a moderate, Central European temperate climate, whilst Perth, Western Australia has a Mediterranean climate. The average temperature difference between a complete year in Kassel and Perth is approximately 9 °C. The numbers for the energy input and flows, e.g. natural gas, can differ for the two locations given the different needs for transport and pre-processing. The higher values for CO_2e-emissions and primary energy demand in Western Australia derive from the mainly coal-based generation of electricity. Here, Germany has a wider mix, including more than 25% of renewable energies (AG Energiebilanzen, 2015).

Operations in the two factories are the same. 30 injection molding machines run 6900 h per year (three-shift operation, no work from Saturday night until Monday morning). Each extruder cylinder has a thermal demand of 4.15 kW_{th}.

3.1. The five energy scenarios

This research considers five cumulative scenarios in order to analyze the capabilities of the companies in the different climate zones. The scenarios are as follows.

- **Base case**: The base case scenario is the worst case in terms of energy efficiency. The molds as well as machines (summing up drive, control, and supporting body) are supplied by the same cooling water. No winter relief by coolers is arranged and therefore the compression chilling machines need to run during all production hours. Due to the poor insulation of the building and associated missing heat recovery, 50 m^3 of heating oil are burnt in the heating system of the building in Kassel, Germany. The factory in Perth, Western Australia does not need to be heated.
- **Simple measures (M 1)**: Measures at the pneumatic system, like the decreasing of 0.5 bar and the detection of leakages, lead to a reduction of the air compressors' energy demand by 20%.The company insulates the walls of the buildings, installs new windows, and uses waste heat from air compressors so that the annual demand for heating oil drops to 13.7 m^3 in Germany (Western Australia: still 0 m^3/a). In order to reduce the chilling machines' running hours, a second cooling system is installed. The cooling temperature coming from the coolers is sufficient for supplying the machines the whole year, subject to the condition that the heat exchangers inside the machines are large enough. Temporarily, coolers can also substitute in place of the remaining chilling machines if the outside temperature drops below 7 °C.
- **Advanced measures (M 2)**: A step beyond the standard approach is the implementation of an energy efficient heating of the molding machines' extruders. Instead of electric barrels, natural gas is burnt to heat up the thermal oil system being used to transport the heat to new barrels on the extruders (Schlüter and Hesselbach, 2010). The old lighting system in the production hall consisting of T8 lamps and conventional ballasts is substituted for modern T8-lamps operated by electronic ballast. The electric energy demand of the illumination decreases by more than 30% (CELMA and ELC, 2011). In this example the effect on the air conditioning system is negligible as it would be in most plastic processing companies because of ambient air temperatures conducted by open windows and a small amount of cooling fans. Nonetheless, the management and the staff desire to reduce overall energy demand of the factory by reducing the associated energy demand of water pumps, the transportation system of the polymers, monitors, computers, and the canteen by 20%.
- **Holistic measures (NG)**: As previously explained, the factory uses molding machines containing hydraulic oil systems. Next to possible exchanges of equipment in that system, tests have proven that the degree of efficiency can be influenced by the oil temperature. A higher oil temperature involves lower oil viscosity leading to lower power demand by the system (Schlüter *et al.*, 2012). In the simulation the cooling water is set 5 °C higher which decreases the machines' energy demand by 3%. Accompanying the increase of the oil temperature, the temperature of the cooling flow rises also which means it is now warm enough to heat the office rooms in Germany during cold weather. Hence, heating oil is no longer required. A second positive holistic energy benefit is a reduced power demand of the coolers outside the production facility.
  Waste heat from the combustion of the natural gas (see M 2) is then used to operate absorption chilling machines instead of using compression technology. However, there is not enough heat for the ACM system. As such, a CHP unit using natural gas is installed, having an electric degree of efficiency of 36% and a thermal one of 49%. Only one part of the waste heat mentioned is hot enough for the ACM. The energy at lower temperature is used to preheat the natural gas burner resulting in some improved energy efficiency.
- **Holistic measures (BM)**: The changes remain as described in the scenarios before. But here the CHP runs on bio-methane gas which has a much smaller negative impact on the environment.

3.2. Economic variables utilized

Typically, enterprises often choose the net present value, the internal rates of return and the time to economic amortization of an investment as indicators of its profitability. Next to the last value

Table 3
These parameters of the energy flows are needed for the simulations (Öko-Institut, 2011; Grote and Feldhusen, 2011).

Parameter	Value		Unit
	Germany	Western Australia	
Greenhouse gas emission of electric power mix	600	898	g CO_2e/kWh_{el}
Greenhouse gas emission of natural gas	233	223	g CO_2e/kWh_{fuel}
Greenhouse gas emission of bio-methane	115	115	g CO_2e/kWh_{fuel}
Greenhouse gas emission of heating oil	316	–	g CO_2e/kWh_{fuel}
Primary energy factor of electric power mix	2.77	2.95	kWh_{pe}/kWh_{el}
Primary energy factor of natural gas	1.11	1.11	kWh_{pe}/kWh_{fuel}
Primary energy factor of bio-methane	0.32	0.32	kWh_{pe}/kWh_{fuel}
Primary energy factor of heating oil	1.18	–	kWh_{pe}/kWh_{fuel}
Heat value of heating oil	10	–	kWh/l–

mentioned, this research uses the modified internal rate of return (MIRR) to express the economic benefit; see Eq. (12) (VDI, 1996).

$$\Sigma(E(n) - C(n)) \cdot (1+i)^{N-t} = A_0 \cdot (1+i_m)^N \tag{13}$$

n stands for the year of utilization and is a whole number while t stands for the whole stretch of time since the installation. The time t can be a digit. The calculation assumes that the annual benefits as the difference between costs $C(n)$ and earnings $E(n)$ of a more energy efficient plant are reinvested in the capital market every year. The basis of this reinvestment is a comparatively low interest rate i. In order to beat the overall performance after the useful life N, the rate of return of an alternative (e.g. real estate or capital market) in opposition to the efficiency investment would have to be at least as high as the MIRR i_m.

3.3. Ecological and economic results

The resulting primary energy demands from the simulations are shown for both locations in Fig. 8.

In the base case the factories have a primary energy demand of about 15.4 GWh/a in Kassel and 15.5 GWh/a in Perth. Table 4 depicts the results for this and the significant energy reductions in the next scenarios. The text that follows focuses on the energy use and explains the changing results with regard to the various scenarios.

It is possible to save a great deal of primary energy by implementing the first measures. The scenario M 1 brings a higher energetic advantage of 18.2% for Kassel (opposed to 12.4% for Perth) because the demand of heating oil is clearly reduced at the European location while it is not required in Perth.

The other measures in M 1 have about the same impact at both factories. In the next step, the advanced measures in the fields of the extruder heating (with natural gas), the illumination and the additional efforts (transportation, canteen etc.) result in a similar reduction of 1.2 GWh/a.

The first holistic scenario (HM NG) leads to a decrease in primary energy demand in both Kassel of 31.4% and Perth of 28.5%. Using bio-methane as an indicative renewable energy fuel for the CHP in the last scenario (HM BM) brings a significant reduction in energy demand for Kassel (−41.1%) and is even more advantageous for Perth (−42.9%). The CO_2-equivalents emissions start at 3447 t per year in Kassel and 4716 t/a in Perth for the base case. Over all scenarios, the percentage of CO_2 reduction is very similar to the actual decrease in primary energy demand.

Table 4
Simulation results for the five scenarios at the locations Kassel (Germany) and Perth (Western Australia) concerning primary energy demand are shown.

Scenario	Reduction of primary energy demand opposed to base case in %	
	Kassel (GER)	Perth (WA)
Base case	–	–
Simple measures (M 1)	18.2	12.4
Advanced measures (M 2)	26.2	20.3
Holistic measures with natural gas (HM HG)	31.4	28.5
Holistic measures with bio-methane (HM BM)	41.1	42.9

4. Discussion

In the simulation results, the simple measures (M 1) have a big impact on the overall energy efficiency. The amount of primary energy saved with advanced measures (M 2) is less than that achieved in M 1. Nevertheless, the potential is still significant. The first holistic approach (HM NG) is able to extend the energetic savings because the economics of these measures is still feasible—but with different outcomes for the two locations. The last scenario (HM BM) shows the major impact of biogenic input into the decentralized power unit.

Approaching the problem holistically, the installation of a CHP running on bio-methane would be a significant investment for both factories. One important reason for this result is the long working time of the cogeneration unit and the absorption chilling machines in Perth associated with the Mediterranean climate, as in this location, the energy efficiency of the heating system for the extruders rises. By taking all thermal energy flows into account more waste heat can be used, thereby adding to the economic benefits of the various technologies.

The different energetic results for the two factories arise largely from the climatic differences and energy sources. In Mediterranean Western Australia, the cogeneration unit and the absorption

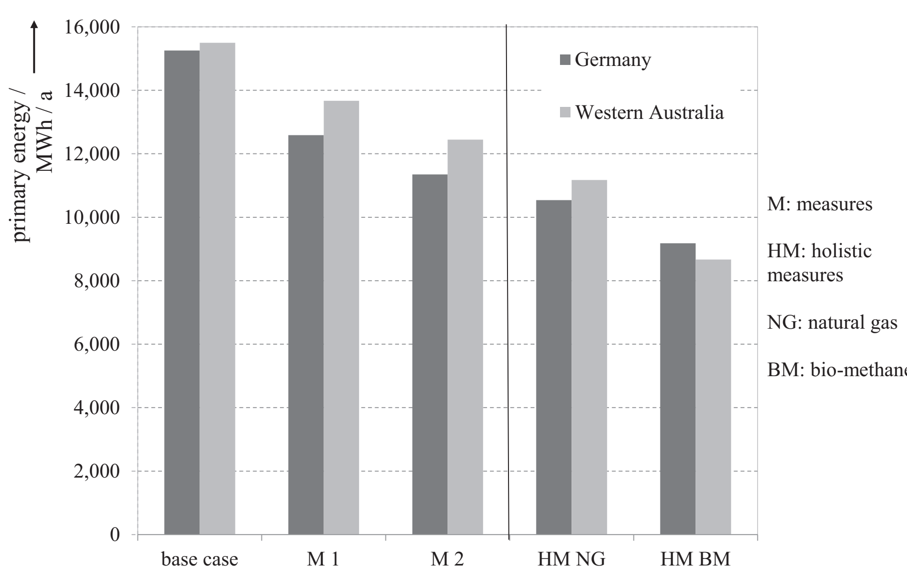

Fig. 8. The comparison of the base case, simple, and advanced measures as well as the holistic measures show that the primary energy demand can potentially be decreased by ca. 41% at the German and ca. 43% at the Western Australian location.

chilling machines are needed for longer time periods during the year (6900 h), and therefore the energy efficiency of the heating system for the extruders rises slightly. In addition, the specific energy mix also strongly influences the primary energy results and carbon emissions. For example, emissions from electric heating are obviously lower in areas with renewable energy like hydro power or wind power, but can be very high in areas with a centralized power supply based mainly on coal, like in China or Western Australia.

Industry choice of power supply is dependent on a variety of factors including local energy prices, energy related laws and regulations (e.g. law of renewable energy, law of cogeneration, "carbon tax"), capability of supplying spare energy to other facilities, and power infrastructure utilized. However, many simple energy saving measures are without cost and easily applied, for example the detection of leakages and the reduction of pressure in the pneumatic system. Most simple measures are based on minor investments in heat recovery via heat exchangers or the installation of separate cooling systems for the molds. In these cases, the economic return or amortization can be as short as one to two years. A system for extruder heating—based on the combustion of natural gas in Germany—can for example result in an amortization of less than three years since the price for electric energy is three times higher for industrial clients in countries like Germany. In this study, the profitability of the CHP cannot be easily assessed due to the assumed contracting of energy purchase in the German case study. Nevertheless, the simulation gives the opportunity to calculate the full cost of the CHP's heat as an alternate energy source within the plastic production systems examined. In the next step, establishing the full costs of energy provision may lead to the determination of the maximum price the CHP's contractors can charge before the investment becomes uneconomic for the factory management (see also Schlüter, 2013).

In the holistic scenarios the absorption chilling machine can access cost-free warm water from the natural gas heating system leading to a drop in the chilling machines' overall heating costs. This information may encourage the management team to invest in the ACM and CHP. A separate combination of an ACM with CHP is too expensive in most cases, particularly in areas where the chilling machine is not utilized fully throughout the entire year (Schlüter, 2013).

In the example above, the thermal oil system (new heating of the extruder barrels, from scenario M 2 on) has a time of amortization of about 2.7 years, which does not sound very attractive from a typical "maximum three years" industry benchmark. On the other hand, the calculated modified internal rate of return is about 16% and could be considered economically attractive (Schlüter, 2013).

The holistic energy assessment framework potentially provides a new business model for establishing a broader energy and economic efficiency assessment method. In Germany, some companies have already adapted their energy demand with increased input from renewable energy options and increasing customer demands for improved energy efficiency and more sustainable products/service offerings.

Summarizing the energetic and ecological results for the different energy scenarios, it can be seen that the holistic approach with scenarios HM NG and HM BM are more economic and more energy efficient than the single energy assessment in scenario M 2. The utilization of waste heat recovery from the hydraulic system is a suitable example of the potential positive benefits associated with a holistic energy assessment.

5. Conclusion

The holistic energy efficiency assessment framework presented in this research provides a novel approach in examining a broader range of factors that influence energy efficiency, with potential for cost savings, and reducing environmental impacts in production activities. Measures like the inclusion of a more detailed examination of waste heat recovery opportunities and the gearing of processes, machines, and infrastructure towards cogeneration-suitable production, potentially provide a more environmental friendly and cost effective solution to enhancing energy efficiency. This method is useful both for reviewing existing production systems as well as in planning for more efficient and sustainable manufacturing and production.

The data-based simulation provided in this research uses five scenarios for comparing the energy efficiency of a German and a Western Australian injection molding factory. In the analysis, the improved capabilities for enhanced energy efficiency were highlighted at both factories examined. The research proves that it is clearly more sustainable to follow the holistic path of energy efficiency assessment than assessing only single source energy systems. Comparing the base scenario and the second holistic scenario, an overwhelming reduction of primary energy of 41% in the German factory and 43% in the Western Australia factory is noted. This efficiency could perhaps be further improved with the initial purchase of more energy efficient machinery.

With the holistic approach, all relevant energy flows are considered in tandem. This view is innovative and could be a solution for enhanced energy efficiency across many production or manufacturing processes. Technologies that could be disregarded on an individual financial case basis could become economically viable when they are considered as part of the whole energy system.

The topic of energy efficiency in industrial processes provides major opportunities for further research and development. Conducting holistic assessments may require greater effort but could be crucial for the long term competitiveness of companies and the sustainability pressures associated with climate change and fossil fuel depletion.

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Nomenclature

0	basis, initial
A	area in m^2
b	basis
ACM	absorption chilling machine
amb	ambient
C	costs in €
ca	Carnot
CCM	compression chilling machine
CHP	combined heat and power plant
$corr$	correction
c_p	specific isobar heat capacity in J/(kg K)
dc	dry coolers

E	earnings in €
EER	energy efficiency ratio
el	electric
ex	exergy
fg	flue gas
$fuel$	fuel
GER	Germany
h	specific enthalpy in J/kg
H_u	lower heating value in J/kg
he	heat exchanger
i	index
i_{mod}	modified rate of return in %
i_{re}	rate of interest for the cash reflux in %
id	ideal
$infeed$	feed line
L	expected useful life
MIRR	modified internal rate of return
$\dot{m}$	mass flow in kg/s
N	useful life in a
n	year of utilization in a
n	index, quantity
ng	natural gas
p	operating point in %
$\dot{Q}$	thermal energy flow in W
$return$	return line
t	time in a
T_{ev}	evaporation temperature in K
T_{con}	condensation temperature in K
T_h	heating temperature in K
th	thermal
U	combined heat transfer in W/(m^2 K)
$\dot{V}$	volume flow in l/s
WA	Western Australia
y	year of usage since installation
$\Delta\vartheta$	delta of temperatures in °C or K
ε	energy efficiency ratio
$\zeta_{ACM,id}$	ideal energy efficiency ratio of an ACM
η	degree of efficiency
ϑ	temperature in °C
τ	factor
χ	performance factor

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