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ORIGINAL RESEARCH

Energy demand and efficiency measures in polymer processing: comparison between temperate and Mediterranean operating plants

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Abstract Polymer processing is an energy-intensive industry. The plastification of polymers requires a high volume of electric power for thermal energy. Electricity based power is the common form of energy in polymer processing and provides obvious potential for a reduction in energy use and costs. Measures to avoid production-based conversion losses, total conversion and transportation losses in energy used all have social, national, economic and business relevance. A bottom-up evaluation of four different production factories in this study assesses the potential for energy use improvements. The resulting theoretical assessment suggested that reducing primary energy demand is the most powerful target for reducing energy intensity in the polymer industry followed by the introduction of improved technologies to raise energy efficiency. The transferability of the conclusions was supported by the comparison between two different geographic locations for polymer production in Germany and Western Australia. The findings of this research suggest potential in their use in 'green' decision-making in the plastics industry.

Keywords Primary energy demand · Energy efficiency within industry · Polymer processing

Introduction

Since 1983 the global plastic industry has grown more than 500 %. In 2012 the world population consumed around 288 million tons of plastics. An annual increase of 3.7 % is forecasted until 2017 [6]. Worrell et al. [24] note that industry contributes directly and indirectly to about 37 % of total global greenhouse gas (GHG) emissions and that in the near term, energy efficiency is potentially the most important and cost-effective means for mitigating emissions.

The Australian plastics and chemicals sector has an annual turnover of around 38.1 billion US$ and contributes 11 billion US$ to the country's gross domestic product. It is the second-largest manufacturing sector in the economy. With more than 50,000 direct employees, the polymer processing industry is a significant contributor fed by extended periods of strong resource growth in Australia over the past 20 years [2]. Similarly, the plastics industry also plays a significant economic role in the German economy with a turnover of around 120 billion US$ and about 363,000 employees. It contributes some 6 % of total domestic industry production [25].

Given the significant power consumption involved in polymer processing the GHG resulting from production are a growing concern [13]. However, despite the technology sophistication of the polymer industry, internationally it still consumes power largely generated by fossil fuel resources. Primary energy demand and potential energy efficiency measures depend on a variety of variables including energy infrastructure provided, chosen

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technology, ambient temperature and climatic zone operation. It is these variables in particular that are of interest to this research. In this paper we compare two very different climatic zones for polymer operations both facing different climate change pressures and review the potential for reducing energy demand and increasing energy efficiency in polymer processing.

The threat of climate change is a factor that could significantly influence energy consumption in international plastics production. Under global warming effect, changes in the intensity and frequency of certain severe weather events have been observed across the world and these events are expected to increase. The IPCC Report on Climate Change (2007) suggests that observed temperature extremes are consistent with a general warming trend—cold days, cold nights and frost have been occurring less frequently in the last 50 years, and hot days, hot nights and heatwaves have been occurring more regularly [12]. As a result, plastics producers across the globe, in the light of these suggested changing operational temperature profiles, may need to consider further ways of reducing energy consumption and increasing energy efficiency.

This study reviews energy demand and efficiency measures in polymer processing in two very different operating environments—in a temperate climate (in Germany) with an average daily temperature of 9 °C with that in a Mediterranean climate (in Western Australia) with an average daily temperature of 18 °C. Under climate change pressures both these operating locations could face increasing periods of hot and or cold weather ([12]: 308) and consequently may need to review energy consumption and the reciprocal demand to improve energy efficiency. Simulations for German and Western Australian polymer production were chosen to represent potential scenarios for energy efficiency enhancement in international polymer production across two very different climatic zones both potentially facing differing climate change pressures but similar energy use challenges.

Rising energy prices also continue to put pressure on the polymer processing industry where energy use accounts for 5–10 % of total production costs [4]. For an industry with many small and medium-sized companies it is increasingly a decisive factor in influencing investment in energy efficiency measures. The high energy intensity of polymer processing relates mainly to the consumption of electricity. The conversion of electric power to thermal energy required by the core process determines the total energy demand.

Due to the central purpose we analysed the energy flows in four factories located in Germany with representative processing types: injection moulding, profile extrusion, blow film and monofil extrusion. These four factories and their associate polymer technologies were then compared and the reasons for the energy consumption differences identified. The various forms of energy demand can be classified with the 'Onion layer model' noted in Fig. 1. This approach recommends a bottom-up analysis of the production areas from the core process to the actual power grid in order to understand total energy consumption. Based on an energy flow analysis the evaluation below links the energy efficiency measures for each onion layer by processing type, production area and the plant location.

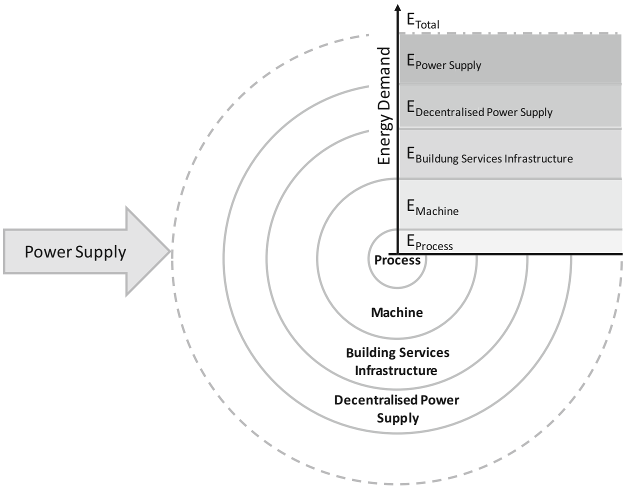

Fig. 1 The onion layer model representing energy demand of a factory [10, 19]

In order to quantify the potential reduction in total primary energy demand, it is assumed that the implementation of all energy efficiency measures is necessary. A simulation of the injection moulding factory including all energy efficiency measures was carried out. The extension of the results of this "best practice" is then discussed. The study also estimated the impact of the various geographic locations on the energy demand. It identifies a range of energy efficiency solutions and also presents economically feasible measures for increasing energy efficiency in the polymer industry in general.

The data sources of the energy flows are from data obtained from real-life polymer production facilities. The "Thermal-Oil" approach was estimated from both Kassel Universities own laboratory measurements and trial period in the real production. In case of the injection moulding the data were evaluated before and after the application of the energy efficiency measures.

Methodology

The purpose of this study is the assessment of the energy demand of different polymer processing technologies. The selected production sites are four medium-sized companies

Table 1 Four analysed factories

ID	Core process	Product	Materials	Process/machine type
moulding	Injection moulding	Lids and capping	Polypropylene, polyethylene, polystyrene	Single- and two-shot injection moulding; hybrid and hydraulic engines
profile_extr	Profile extrusion	Insulating profiles for windows	Polyamide, additives	Mono- and dual-screw extruders
film_extr	Blow film extrusion	Plastic films	Polyethylene, additives	Blow film extruders; single- and multi-layer extrusion
monofil_extr	Monofil extrusion	Monofil threads	Mainly polyamide, polyethylene and, additives	Monofil extrusion

located in Hesse (state, Germany) with a highly specialised manufacturing structure (Table 1).

A limited product range is typical in polymer processing. The high scalability and flexibility of the core process is a determining factor for production volumes and revenue. Consequently, the manufacturing structure is lean and is usually reduced to one process type. However, at the same time the variety of products produced is high often requiring post-treatment and selected customisation. In the following discussion, single product factories are briefly introduced. In order to simplify the data identification, the factories are given an ID (Table 1).

The factory "moulding" produces plastic lids and capping for packaging in the food and tobacco industry. Due to health and safety restrictions set by the purchaser, the polymers do not include any additives. The core process is injection moulding. Forty injection moulding machines are situated in the manufacturing area. They have different size and construction types (hydraulic and hybrid engines as well as single- and two-shot-moulding techniques). In contrast to the extrusion moulding, injection moulding is a discontinuous process with defined cycle times. The additional post-treatment includes the insertion of paper or aluminium gaskets and packaging. Some of the robots for the customisation treatments are permanently installed. Others are portable ensuring high flexibility for production [14].

The second analysed factory "profile-extr" specialises in the extrusion of the insulating profiles for aluminium window frames. The profiles comprised a mixture of different synthetic components. The materials involved are based mostly on polyamide. This factory dries the polymer granules before the extrusion and stores it temporarily. The additives are necessary for the improvement of the thermal properties of the polyamide. The production system includes six extrusion machines. The number of screws (one or two) and their diameter are the main differences between the extruder processes. Directly after the continuous processing the profiles are cut into single pieces. Next additional features like adhesive ribbon, wire and/or polyurethane foam are inserted into the profiles. Other customising processes include punching and drilling.

The blow film extrusion is the core process for the factory "film_extr". Single- and multi-layer films are extruded from the granules mainly consisting of polyethylene. Similar to the *profile_extr* polymer they are dried before processing. There are 13 blow film extruders with one or multiple screws for the multi-layer films. The films are used for the manufacturing of the bags and protective foils in the automotive industry. The customisation is limited to roll up, cutting by welding and packaging processes.

Factory "monofil_extr" produces polymer threads by monofil extrusion. Different polymers can be used for the threads and through additives the properties and chemical resistances are varied. This production also requires the pre-treatment of the polymers to ensure required moisture content. The number of holes in the die plate allows simultaneous extrusion of numerous threads on 17 production lines. Each production line includes several post-treatment steps. The threads are cooled in water tanks and afterwards stretched between drafting units that run at different speeds. The fixation is located in a hot air chamber. Afterwards the threads are rolled up.

Assessment approach for energy efficiency

The comparison of the energy efficiency of different polymer processing methodologies across the plants in two very different climatic zones in Germany (temperate) and Western Australia (Mediterranean) requires benchmark parameters. Energy efficiency is defined as the ratio between energy consumption and the use of the energy in a system [10]. Energy demand is a key dimension for the evaluation of the energy efficiency in production.

Given different usable energy (exergy) forms, a direct comparison of different energy forms like thermal or mechanical energy is not possible. For the generation of these energy forms, several technical solutions are available. As a result, the environmental impact of a kilowatt

Table 2 Primary energy factors

Form of energy	Germany	Western Australia	Unit
Mix of electric grid	2.77[a]	2.95[a]	$\mathrm{kWh_{pe}}$ per $\mathrm{kWh_{el}}$
Heating oil	1.18[b]		$\mathrm{kWh_{pe}}$ per $\mathrm{kWh_{th}}$

pe primary energy, *el* electric energy, *th* thermal energy

[a] IINAS [11]; [b] PE International AG [16]

hour of final energy varies. A benchmark of primary energy input was considered reasonable for this benchmark comparison.

Primary energy is defined as total fossil fuel and renewable energy resource use. Given the required energy transportation to the site and the conversion process in a power plant, some transaction losses of energy occur. The final energy input is calculated from the residual energy use after the losses of conversion and then transport to the customer. The final energy input can be available as electric power but also as fuel or natural gas, etc. The remaining useful energy is the energy used in the process: e.g. light, mechanical or thermal energy [13, 15].

The primary energy factor is the ratio between the primary energy from the energy sources (fossil fuel as well as renewable) and the total energy used. Depending on the mix of energy sources used, the primary energy factor varies by country. Table 2 summarises the relevant primary energy factors used in this study.

The lower factor of the German electric grid is because 23.4 % of power generation is from renewable energy sources [3]. In contrast, the total amount of electricity delivered by renewable energies in Australia is only 13.4 % [5].

A comparison of polymer processing at different production locations requires further definition of the system. Due to the focus on the technological evaluation and the identification of energy efficiency measures, the system boundaries are set as "gate-to-gate". The energy flow assessments contain all demands within the physical factory area. The energy use evaluation is based on annual monitoring values and additionally on measurements from the machinery asset monitors. These measurements were carried out at time intervals of up to 24 h. Results were verified and extrapolated values were determined by a top-down calculation. The data for Western Australia were estimated in cooperation with the Curtin University in Perth, Australia.

Results

As mentioned above, electricity, heating oil and natural gas are purchased to meet production demands (Table 3). The annual power consumption of the four plants is between 3.8 and 5.6 $\mathrm{GWh_{el}}$. The absolute volumes of heating oil and natural gas for supporting services like space heating were of secondary importance. As discussed previously other energy sources like fuel for transportation are not considered within the boundaries of this study.

In order to identify more clearly appropriate energy efficiency measures, more detailed information concerning total energy demand was required. Four categories of process were highlighted:

1. pre-treatment and technical support processes,
2. core process,
3. post-treatment and customising and
4. others.

The first group includes all material treatments to achieve the quality properties that are necessary for the core process. Further the energy demand of the assets that supply the polymer processing machines is also assigned to this category. In addition, the primary energy demand resulting from the usage of the heating oil and natural gas was allocated to "technical support". The core process describes only the direct energy demand of the extrusion and injection moulding machines including the engines, melting units (extruder or screw cylinder including moulds with hot runner system), the temperature control unit and the electronics for driving and measuring the system. All customising and treatment processes like cutting and packaging of the end product are considered in the third category. The last group "other" includes the energy demand for related production services including non-production areas, e.g. administration, maintenance and control buildings which require electricity for illumination, electronic devices in working areas as well as in social spaces like kitchens and toilets.

Calculation of primary energy demand

The weighting of the primary energy demand in each process category in the assessed factories is shown below (Fig. 2). The total primary energy demand is between 12.9 $\mathrm{GWh_{pe}}$ in *profile_extr* and 19.3 $\mathrm{GWh_{pe}}$ in film_extr. The relative weighting allocation highlights, as expected, that total primary energy demand is significantly influenced by electric power consumption. In terms of energy efficiency measures the concepts for the reduction of the electricity demand assumes a higher potential.

Table 3 Annual demand of energy sources

Form of energy	Unit	moulding	profile_extr	film_extr	monofil_extr
Electric power	GWh_{el} per year	5.3	3.8	5.6	4.8
Heating oil	Thousand litres	13	49	86	49

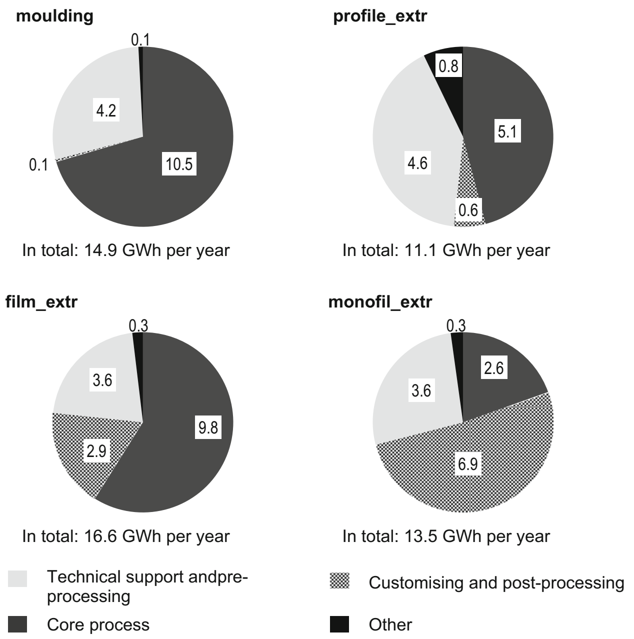

Fig. 2 Primary energy demand by polymer processing technology by processing steps in GWh_{pe}

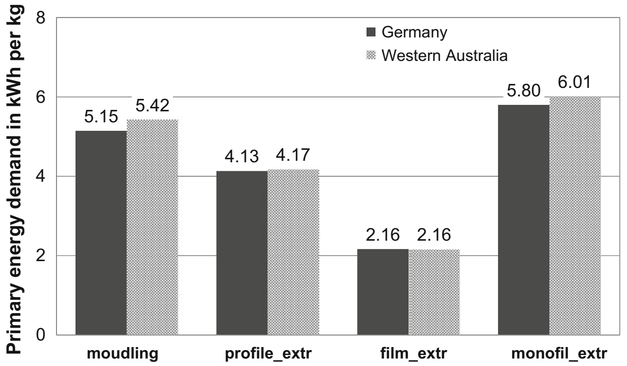

Fig. 3 Specific primary energy demand for the four process technologies given production parameters for German and Western Australian climatic location

Except for the factory monofil_extr, the core process has the highest energy use share. This is due to the fact that the engines requiring the energy demand are mainly driven by the melting and moulding process. From an efficiency point of view, especially the conversion of power to heat, a less effective energy form, does not appear suitable. The heat has less exergy than electricity and as a consequence is less useful in meeting energy demand.

The energy demand of technical support and pre-processing stages involves supply aggregates for thermal energy (cooling systems and compressed air) as well as several treatments for the granulate (drying, transportation by vacuum pumps and so on). The higher energy consumption of the factories *moudling*, *film_extr* and *monofil_extr* is due to their use of compressed air. The injection moulding process runs discontinuously therefore the items are released, moved and packed by different pneumatic robots. The *film_extr* process requires compressed air for blowing. The demand of *monofil_extr* is analogous to the *moudling* and *film_extr* processes. The profile extrusion has a high number of manual applications and only few, like screw driving, where compressed air is required.

The power needed for customising and post-processing is particularly important in the *monofil_extr* process. These treatment steps are required by the monofils, which involve multiple cooling and warming process stages. Like in the plastification process, electricity is used for the generation of thermal energy. In contrast, the post-processing process in *moulding* is negligible. For the customisation stages, pneumatic packaging robots are utilised. Their power demand is low in comparison to the compressed air. Energy use of the compressors is assigned as "technical support".

The energy efficiency of the four plastic process technologies was assessed by means of the specific primary energy demand per kg of plastic. Figure 3 shows the different resulting numbers for German and Western Australian production. The specific demand varies between 2.16 and 6.01 kWh_{pe} per kg. However, a competitive comparison between the processes is not the scope. The difference between the processes is mainly due to their production characteristics including running time, number of shut downs, mould exchanges and warm-ups.

In three cases the specific primary energy demand of Western Australian production is higher than in the German examples. But in total the resulting variances between the factories are quite negligible. This suggests a very similar specific energy demand by each plant with the primary energy factors of both countries seen to be comparable. It is surmised therefore that the process technology maybe a more decisive feature in influencing energy efficiency measures than the geographic/climatic location. Therefore the energy efficiency measures described below could be applied in each factory. The following discussion and research will focus on energy efficiency potential in measured, simulated and implemented results for only injection moulding production in both climatic zones.

Locations and possible measures

The state of Hesse is located in the middle of Germany and is a temperate climatic zone in Central Europe. Its average day time temperature is about 9 °C. The chosen comparison operating reference is in Perth, Western Australia, which has a Mediterranean climate and long hot summers which result in an average day time temperature of around 18 °C [21].

As a result, polymer processing factories in these two different geographical and climatic locations may require different types of energy efficiency measures in order to help improve overall energy efficiency and reduce primary energy demand. Furthermore, any increase in extended periods of hot or cold weather under changing climate conditions, may infer the need for increased adaptive capacity in maintaining energy efficiency and or reducing primary energy demand.

Similar measures for both regions

The magnitude of order of these energy efficiency changes corresponds to the onion layer model illustrated in Sect. 2. This section gives an overview concerning the measures for increasing the energy efficiency of injection moudling process and production assets, with the potential efficiency changes in the infrastructure noted later in discussion.

Process and machine

In order to enable short cycle times, the moulds of the machines need to be supplied with cold water at an average temperature of 10 °C. In contrast, the drive units of the injection moulding machines do not require these low temperature levels.

The thermal energy demand of the barrels of the injection moulding machines is similar in both regions. These cylinders need external heating depending on the size and the flow rate of the polymer to be plasticised [1]. In this case the usage of natural gas and its enhanced exergy potential may be a more suitable energy efficiency measure. The natural gas primary energy factor before burning is 1.11 in both countries [11]. The “Sustainable Products and Processes” research department at the University of Kassel has developed a system where the combustion of natural gas can heat up thermal oil. The thermal oil circulates within a ring system of heat exchangers on the barrels and the heater as well as on the pipes. Early feasibility tests of this technological approach resulted in the same quality of products in injection moulding and blow extrusion than those generated using electricity heating for the melting of the polymers. Apart from initial costs and the space required for the pipe system, this measure has several advantages:

- an increase in primary energy efficiency associated with the heating of the barrels,
- improved cost efficiency (in Germany electric energy is about three times more expensive than natural gas),
- better control and less overshooting of the temperatures inside the barrel [20, 21].

The simulation and trials in the real factory as a part of a further project at the University of Kassel proved the application of this approach for blow moulding processing. Here the thermal oil system was installed at a blow film extruder. Testing of the thermal oil flow using natural gas resulted in the heating of some extruder zones and the cooling down of others. In combination with improved insulation and the substitution of electric power with natural gas, savings of primary energy by 30–40 % could be realised in the research trials [18].

Infrastructure

Instead of using chilling machines the cooling fluid for the machines (drives, controls, etc.) can also be cooled down with free coolers. This form of process cooling works well in Germany. In Western Australia the summer can be very hot and the cooling fluiđs temperature becomes too warm. Consequently, the company must replace the machines’ heat exchangers with ones that have a larger surface area to allow appropriate cooling. Another option would be the application of coolers with vaporisation potential or chilling machines on hot days. The cooling system also provides capacity for heat recovery, for example at the condenser of the chilling machines or as replacement for coolers exchanging thermal energy to the environment.

Some plastic processing factories use compressed air for motion during packaging or other post-processing. The supply and distribution of compressed air is not efficient. The effectiveness is only 3–4 % from primary to useful energy [9]. The approach for optimisation involves compressor technologies, the distribution network and the level of operating pressure. Additionally, the large amount of waste heat from the compressors can be also used for heating. In some cases a complete substitution of the pneumatic system is even possible with electro-mechanical devices [17].

Different measures for the regions

In terms of infrastructure and energy supply the implementation of the following energy efficiency measures creates different outcomes for injection moulding processing at the two different plant locations.

Infrastructure

Another efficiency potential for both countries could be the optimisation of the cooling process of the moulds. It is also possible to cool the moulds down by coolers instead of the energy-intensive chilling machines. The weather conditions in central Europe allow this only about one-third of the year. This is because the fluid temperature is required to be maintained between 10 and 15 °C, depending on the process. However, in Western Australia outside temperatures may not drop sufficiently low for long enough to justify this approach.

Energy supply

Although the processing machines emit a lot of heat, central Europe's plastic producing companies still have a certain demand for the heating of offices and workshops in winter. Therefore, a lot of factories in Germany use additional fossil heating at this time. In contrast, only a few heating systems are installed in Western Australia given the Mediterranean climate [19]. Plastic processing factories in Europe therefore have some opportunity for heat recovery at production temperature levels of 70 and 80 °C helping to reduce fossil fuel heating demand.

The installation of a Combined Heat and Power Plant (CHP) can offer a major contribution to an increase of energy efficiency in a company. In Germany the economic feasibility is largely based on annual running hours of at least 4500–5500 h. The essential factor for profitability is the demand for heat in the factory. The operation of the thermal oil system mentioned earlier represents an important new thermal sink. Here, the application of a CHP with turbo-chargers could be a reasonable energy efficiency option. An additional heat exchanger in the exhaust gas flow would enable the usage of the high temperatures in the thermal oil circuit.

Another possible heat sink is the absorption chilling process as a supplement or replacement for the compression technology. In winter the waste heat from the engine of the CHP plant is usually used for heating. In summer the heating demand decreases. Therefore, this waste heat could be used for an absorption chilling process. In this case during winter there will be less running hours of the chillers. At the same time the annual full load hours of the CHP rises. Due to the higher potential of winter energy relief of cooling in Europe, the potential benefits from CHP in Western Australia may have even higher energetic potential.

Discussion

The combination of energy efficiency measures considered will always involve a compromise between technological solution and economic benefits for each individual production site. This efficiency depends on a wide number of factors including:

- existing equipment,
- size,
- energy demand,
- the ambient temperature of the operating environment,
- the capital and
- human resources of the production facility.

The example of injection moulding given in this analysis has been optimised in terms of energy efficiency and the success of the implemented measures reviewed. Whilst the conditions in Perth for the manufacturing processes have been simulated, the suggested results are also indicative of energy efficiency benefits. In the following discussion suggested energy efficiency measures for injection moulding production in particular are now reviewed:

- The heating of the extruders: natural gas instead of electric energy is used for the thermal oil system. The new system includes a pre-heating of the inlet air.
- Relief for the chilling machines whenever the outside temperature is lower than 7 °C.
- The drivers of the machines are cooled by water cooling. Only the moulds are supplied with the cold water from chilling machines.
- One-third of the cold temperature energy required for processing comes from an absorption chilling machine which receives cost-free heat from the heat recovery from the natural gas-heating.
- The balance of the heat needed for the absorption chilling machine comes from cogeneration in a block heat and power plant which runs on natural gas.
- Production facility heating systems (building and use water) can also benefit from heat recovery from the pneumatic system. However, in Western Australia this amount of heating energy is too low for reasonable implementation [22].

Overall and as a result of the above energy efficiency initiatives, the injection moulding plant in Germany can save 56 % of its primary energy. In Western Australia the improvement is potentially 52 % of primary energy. Figure 4 displays the results of the primary energy demand savings for the simulated injection moulding factories [23].

In both countries the thermal oil system has a major impact. The improvements concerning the heating demand, e.g. isolation and heat recovery, are however more important in Germany. Irrespective of the factory location the savings of primary energy can be raised significantly with the use of combustion biofuel in the decentralised power unit.

The energetic optimisation of the polymer plastification with thermal oil heating system is a specific technological

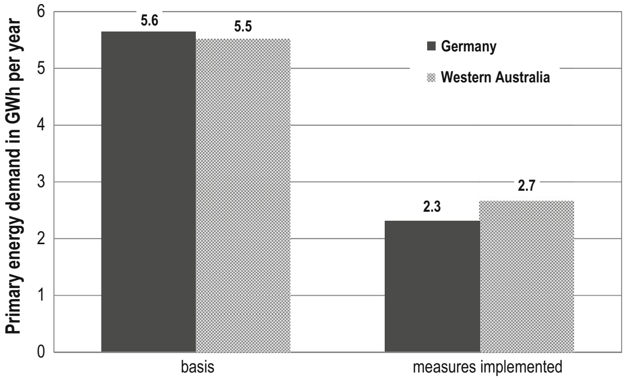

Fig. 4 Simulated results for comparing energy demand of injection moulding factory under German and Western Australian climate conditions before and after implementing energy efficiency measures

solution for this branch. The general idea to avoid multiple conversion of thermal energy and the associated energy losses (coal to thermal energy; thermal energy to electricity; electric power transport and transformation) can be applied to many other processes.

The described energy efficiency measures for compressed air and cooling could also be extended to other industrial sectors. The decentralisation of the energy supply with CHP requires thermal energy sinks, e.g. washing, drying or other thermal pre- and post-treatment processes. These can easily be found in automotive, metal processing as well as pharmaceutical and nutrition processing and production [7].

The core processes of polymer processing are energetically quite lean and therefore the differences in the primary energy demand were mainly identified in the technical support processes, both pre- and post-treatment; whilst the economic pressure on energy efficiency measures increase as energy costs rise as a percentage of total manufacturing costs. Although this research does not investigate the direct impacts of climate change on polymer processing energy use or energy efficiency, it does suggest that there are potential areas for enhanced measures as waste heat recovery or smart cooling concepts that can help to reduce primary energy demand and improve overall energy efficiency.

The onion layer model evaluation methodology has been a simple but effective approach in estimating the energy flows and the systematic identification of energy efficiency potential [8]. As such, increasing pressures on greenhouse gas management together with rising energy prices and operating conditions under global climate change, do suggest an important need to review both primary energy use and latent energy efficiency potential in production processes.

Conclusion

This study has evaluated four different polymer factories and simulated one of these factories in two climatic zones in order to review the potential for primary energy demand reduction and enhanced energy efficiency under different operating conditions. The energy efficiency initiatives investigated in this research highlight the benefits of the explained measures in two different climatic zones—one characterised by cold temperate weather and the other by warm, dry Mediterranean climate. These results may become increasingly valuable to polymer processors under conditions of climate change. Whilst such energy efficiency strategies may have early economic advantages, in the future, such initiatives may be required or even be mandatory given increasing pressures from rising energy prices, changes in operating conditions under climate change and GHG regulatory programs.

One of the main challenges faced in reducing energy demand is related to the current dominant utilisation of electric power as the main energy source for polymer production processes internationally. Strategies for the reduction of primary energy demand in this research were based on a systemic assessment of the energy use highlighted in the onion layer energy model reviewed.

Future energy challenges will involve analyses similar to that utilised in this research, but will also need to include both economic and environmental benefits arising from combining different energy efficiency measures across several production levels and any resulting modifications to these processes and existing assets. Life cycle assessments may assist in determining these trade-offs.

The implementation of some of the described measures in this simulation study did provide energy efficiency improvements for the injection moulding examples provided. This research reflects the potential to increase energy efficiency in polymer processing across different climatic zones and may well have lessons for other energy-intensive industries. However, it is also important to consider the sustainability outcomes associated with these energy efficiency management initiatives. Increasing energy efficiency awareness and providing reliable measures to help reduce primary energy demand will also help to reduce greenhouse gas emissions that then could lead to significant economic and corporate stewardship competitive advantage.

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