Effects of Implementing Efficiency Techniques in the Plastics Industry in Germany and Western Australia – A Comparative Modelling Assessment.

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Abstract

Plastics manufacturing is an important industry in many countries. Energy consumption in particular can be very high. Energy efficiency is an increasing area of management interest given pricing pressures on manufacturing companies around the world. In some cases simulation can help to predict the results of implementing different technologies to improve energy efficiencies. This paper focuses on the results of a simulation model which deals with the substitution of electric power with natural gas and the cooling of moulds by absorption chillers in plastics production. The methodology reviewed can result in significant reductions in energy demand and is also valuable when energy requirements for heating purposes are relevant. Germany and Western Australia both represent different climatic regions, but the modelling assessment on production facilities in both countries highlights the benefits of taking a whole systems approach to energy saving and energy efficiency in plastic production.

Keywords:

Climatic Regions; Energy Efficiency; Plastics Industry; Sustainable Manufacturing

1 INTRODUCTION

Given current and expected future changes in the energy policy, energy efficiency is more and more becoming a commercial and political concern. It is an increasing area of management interest in manufacturing companies around the world. The managers regard the cost effectiveness of their production while researchers are interested in finding ways to minimise the pollution of environment.

Additionally, political focus is being given to energy efficiency internationally. One goal of the German government is the reduction of greenhouse gases by 40 % until 2020 on the basis of 1990's data [1]. Australia recently raised a tax on the emission of carbon dioxide and has committed to reducing its emissions by between 5-15% or 25% of 2000 levels by 2020 [2].

According to VAN HEUR AND VERHEIJEN 2009 energy consumption in the plastics processing industry is significant and specific to the processing technique. Energy consumption is attributable to:

- Melting of raw materials
- Cooling
- Driving peripheral equipment such as grinders, compressors, pumps, pre-driers, mixers etc.
- Vacuum formation of semi-manufactured products.

They note that energy consumption depends on a variety of factors, for example

- Type and characteristics of the plastic
- Design, complexity, and size of the end product
- Techniques used for the shaping of the product
- Cycle time
- The size of the plant
- Outside temperature [3].

Efficiency practices in the plastics industry can cover a number of processes – energy use, energy recovery, material recycling and waste reuse. As energy is seen to be the largest component having a life cycle impact on the environment, an energy analysis is a good initial tool to estimate the ecological burden from plastic production and to highlight those areas of process or technology where potential improvements can be found.

PATEL 2003 made an assessment of CO_2 emissions from cradle to factory gate of energy consumption in the plastics industry in Germany. He indicated that the choice of feed-stock, integration in the energy system, the type and quality of the process and the operating mode (good housekeeping) all have a considerable effect on energy demand.[4]

Furthermore, capturing and reusing heat generated in the production process, combined with equipment upgrades and process innovation, are further examples of how a higher level of energy efficiency can improve profitability and market competitiveness.

1.1 Simulation as one key

Whilst renewable energy policies have increased considerably across the globe, energy efficiency initiatives have also become a very important focus. It gives the possibility to raise the cost effectiveness of companies and to obtain competitive advantages. In order to get to this point, modelling simulation can help predict the results of implementing different technologies. It has played a significant role in science and economics in the last years.

1.2 Climatic differences between regions

Perth, as the capital of Western Australia has an average temperature of around 18 °C. It has a Mediterranean climate of long hot summers and cool winters. The average temperature of Kassel, a city in the middle of Germany, is approximately 10 °C below. The country is situated in the moderate climate zone of Central Europe.

2 GOOD REASONS FOR A CHANGE

The plastics producing industry is an important industry in lot of countries across the world, including Germany and Western Australia. The world’s plastics industry has produced about 265 Mio. tons of polymer in 2010 [5]. In Germany, the processing of polymers results in annual sales of around 55.9 Bill. € and has around 292,000 employees in 2,735 enterprises [6]. Plastic industry energy costs extend from 5 to 10 % of the entire production costs [7]. The capabilities for energy efficiency are therefore are important from economic, social and energetic points of view. In the field of the plastic processing, for example, injection moulding, extrusion companies, foil producers (calendering) or the processors of synthetic resins and foams all rely on significant energy input in their production activities [8].

In injection moulding factories the machines are the main consumers of energy given their cooling as well as heating processing and because of the actuation of electric and hydraulic aggregates. It is quite common for companies that use electric power to change it into thermal power despite the fact that this is not efficient or cost effective. From an energetic point of view the chain of transformation from primary to useful energy is too long and therefore inefficient. Transforming gases locally offers the potential to save primary energy – and to reduce emissions of greenhouse gases.

Table 1 presents primary energy factors as well as carbon dioxide equivalents for different types of end energy in Germany and Western Australia. Based on today’s infrastructure, statements for biomethane are only provided for Germany.

Table 1: Primary energy (pe) factors and carbon dioxide equivalents in Germany (GER) and Western Australia (WA), ee: end energy [9]

Form of power	Primary energy factor in KWh_{pe}/kWh_{ee}	Emissions in kg_{CO2e}/kWh_{ee}
el. grid GER	2.77	0.600
el. grid WA	2.95	0.898
natural gas GER*	1.11	0.233
natural gas WA*	1.11	0.223
biomethane GER*	0.32	0.115

* basis: heating value

The above data represents the region’s mix of energy types. Higher emissions associated with WA’s electric grid derive from the high percentage of coal used in power production. A reduction in power demand can also provide commercial benefits: For a lot of German middle sized plastic processors, electric power is about 2.5 to 3 times more expensive than natural gas. In Western Australia the conditions are similar [10].

In the next steps this paper shows ways to substitute inefficient and expensive technologies through the modelling simulations of alternative power source options and changes in production process.

3 USAGE OF GAS INSTEAD OF ELECTRIC POWER

Plastics producers require significant energy for heating processes, e. g. for the barrels or for the hot runners inside the moulds. Normally, they use electric energy for this purpose. As can be seen in Table 1, the decentralised combustion of gas could provide efficiency and cost benefits both in Germany and Australia. A testing unit at the University of Kassel has shown feasibility of a gas-fired heating of extruder barrels on an injection moulding machine.

The tempering unit developed mainly contains a burner for natural gas, two heat exchangers and a control system. After the combustion the flue gas heats up a mass flow of thermal oil supplying the barrels with heat at a temperature level of 200 to 300 °C. A second heat exchanger enables the extraction of more heat from the flue gas flow by transferring it to a water mass flow. Experiments have proved that it can be heated up to temperatures near the water’s boiling point, which makes it valuable for heat exchange.

However the idea of a hot thermal oil system for barrels is not new. In the middle of the 20th century it could already be seen in factories, but vanished because electric collars were often easier to handle. Rising prices for energy is making managers think about smarter energy management options. The heating of the moulds by gas is a possibility. The products have the same quality compared with the current production technology. The decentralised solution however may offer new opportunities, especially for polymers that have a small processing latitude, for example special bioplastics. A tempering unit could be installed with or without the application of the second heat exchanger. The model described in the following discussion and theoretical modelling includes it and thereby connects different decentralised supply units.

4 SIMULATION MODELLING

While producing, the moulding machines transform electric energy into thermal energy. One part of this waste heat goes to the ambient air. The rest is caught by water mass flows. Coolers are able to convert the waste heat very efficiently. But at some parts of the process, e. g. the mould, the water coldness must not exceed a certain temperature with companies using chilling machines to maintain the required temperature profile. Compression chillers (CCM) of today’s industrial stock need usually require one kWh_{el} to transform electric energy into 3 kWh of coldness [11]. Absorption chillers (ACM) however can use waste heat instead. As shown in Schlüter et al. 2011, the combination of gas-fired heating of extruders is both efficient and cost effective [12].

During winter production coolers can be used instead of chilling machines. Overall, the connections described can lead to an efficient and dynamic system, see Fig. 1.

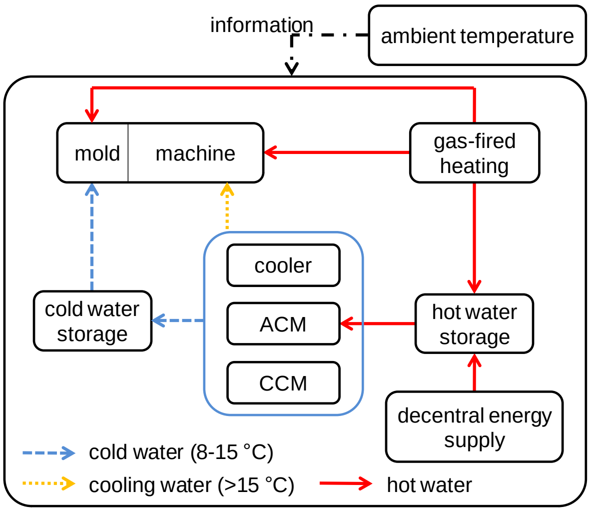

Fig. 1: Dynamic system of the model, modified from [12]

The simulation software used is MATLAB®/Simulink®. The system's simulation model was validated with measurements from industry utilised machines and devices in the university and in the factory of a project partner.

The system model consists of different submodels. The following discussion explains important submodels and shows results for two plastics producing factories in WA and Germany.

4.1 Submodels

Injection moulding machines

The basis for modelling the production machines is a node model which helps to transform partial differential equations into *n* simple differential equations. The number *n* differs from the number of nodes chosen. By segmenting the machines into a body which can be represented by the node model it is possible to simulate those complex bodies [13].

The model machine consists of four partitions:

- Mould
- Extruder barrel
- Actuation system
- Control inclusive others

Inside the barrel the mass flow of polymer gets heated up. After being injected it exchanges thermal energy into the mould. Here cold water is needed in order to cool down the mould. A second cooling flow goes to the actuation system and the control. Every partition of the machine is subject to the law of conservation of energy, see equation 1.

$$mc\,\frac{\partial\vartheta}{\partial t} = P_{\mathrm{in}} + \dot{Q}_{\mathrm{in}} + \dot{Q}_{\mathrm{cool}} + \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{rad}} + \dot{Q}_{\mathrm{poly}} \quad (1)$$

with:

$P_{in}, \dot{Q}_{in}$: input of electric or thermal power

$\dot{Q}_{\mathrm{cool}}$: thermal cooling power

$\dot{Q}_{\mathrm{conv}}$: thermal convection power

$\dot{Q}_{\mathrm{rad}}$: thermal radiation power

$\dot{Q}_{\mathrm{poly}}$: thermal power of leaving polymer

The resulting non-steady-state was validated at a small moulding machine at University of Kassel. For the whole system the water flows of larger machines are of more interest. Direct measurements in a project partner factory lead to a second review for the machine used later.

Thermal energy storage

An important component in a thermal system is the storage of energy. For this purpose, the node construction is used again to model a storage based on several layers. Each of them contains a node in the layer's middle. Energy streams enter the body via a heat exchanger or via open entrances. Between the layers natural convection and conduction lead to a transfer of thermal energy. In the case of a usage of the open entrance, forced convection occurs. Two graphs for a simulation and the measurement at a 300 l-storage containing water are included in Fig. 2.

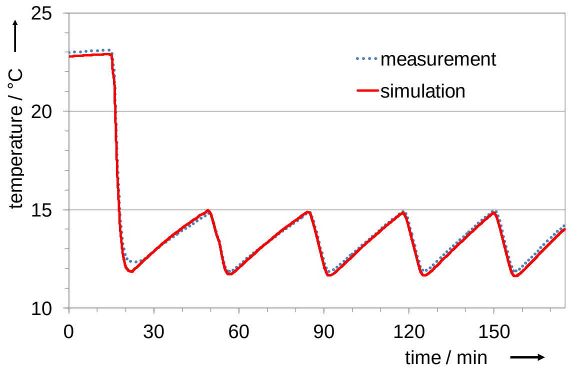

Fig. 2: Part of a validation of a 300 l-storage, combination with a compression chilling machine

The model has been validated on different sizes of energy storage. The reviews also included a combination with another storage as well as a combination with a decentralised energy supply unit.

Tempering unit

Inside an ideal gas-fired tempering unit, the thermal energy of the burnt gas is forwarded to a flow of flue gas. It crosses two heat exchangers on its way out and therefore can heat up the flow of thermal oil, which goes onto the extruder barrels, and a flow of water, which might for instance be used in a sorption chilling machine. Equation 2 presents the coherence between the combustion of fuel (B), the energy flows of thermal oil (oil), water (H_2O) and exhaust gas (ex) as well as a component of loss from the tempering unit.

$$\dot{Q}_{\mathrm{B}} = \dot{Q}_{\mathrm{oil}} + \dot{Q}_{\mathrm{H_2O}} + \dot{Q}_{\mathrm{ex}} + \dot{Q}_{\mathrm{loss}} \quad (2)$$

In the next step the simulation calculates the amounts of $\dot{Q}_{\mathrm{oil}}$ and $\dot{Q}_{\mathrm{H_2O}}$. Among other things, they depend on the unit's efficiency assumed, the temperatures of the flow gas before and after the heat exchangers and on the physical conditions of the incoming fluids.

Combined block heat and power plant (CHP)

The command variable of the combined block heat and power plant (CHP) is the thermal energy needed for the absorption chillers. Simultaneously generated electric power E_{gen}, see equation 3, affects the economic and environmental balance. It helps to release the central power grid of the utility.

$$E_{\mathrm{gen}} = \int_{i=1}^{n} \frac{\partial E_B}{\partial t} \cdot \eta_{el} \qquad (3)$$

η_{el} is the electric degree of efficiency. The calculations for the end energy are identical for cogeneration based on biomethane or natural gas. However, the primary energy needed differs. According to equation 4 the overall efficiency is the sum of the electrical and the thermal (th) component.

$$\eta_{\Sigma} = \eta_{\mathrm{th}} + \eta_{\mathrm{el}} \qquad (4)$$

The University of Kassel has developed and built a decentralized energy supply unit containing a CHP as its heart. Based on own measurements and manufacturers' information, it is assumed that the overall efficiency is constant for the particular CHP used. The tests also allowed the formation of an empirical equation for electric power depending on the machine's operation point.

4.2 The whole system model and results

After the review of the individual submodels, they were combined for assessment. The first level of the whole system is presented in Fig. 3.

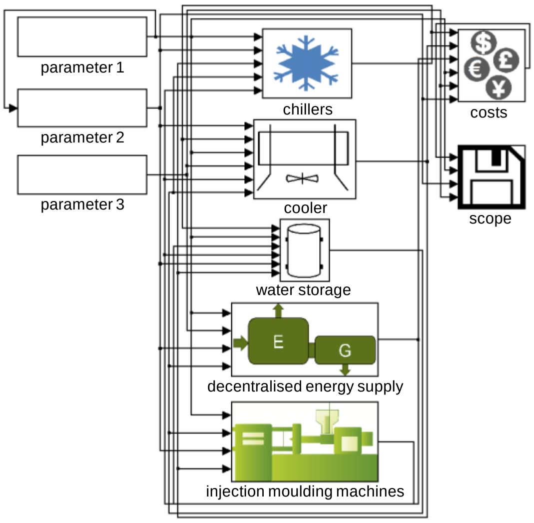

Fig. 3: First level of the system model

The exemplary factory produces with 30 injection moulding machines 24 hours 6 days a week (except Sunday), which leads to 6,900 h/a. In the basis scenario the company uses compression chilling machines only. There is one shared cooling flow for the moulds and the machines. The heating of the extruder barrels is electric. The following steps of optimization uncover potential efficiencies the thermal supply of the machinery.

Optimisation a: The company segregates the cooling of the mould from the machines. The cooling fluid for the machines can be warmer. Additionally, if ambient temperatures are below 7 °C, it is possible to use coolers instead of chillers (winter release).

Optimisation b: On top, the company starts to heat the extruders by combustion of natural gas.

Optimisation c: Additionally, the factory uses more of the energy in the tempering unit's waste gas by sending a water flow through it. Transforming the heat, one absorption chiller can supply one third of the overall coldness. The rest of the needed heat derives from a CHP on the basis of natural gas.

Optimisation d: Instead of natural gas, the companies change to biomethane for the CHP. This is a future scenario for Western Australia. That is why the data of the Geman biomethane mix is assumed for both countries. The extruder barrels stay heated by natural gas.

Fig. 4 presents results for the CO_2e-emission associated with plastics production in Kassel and Perth.

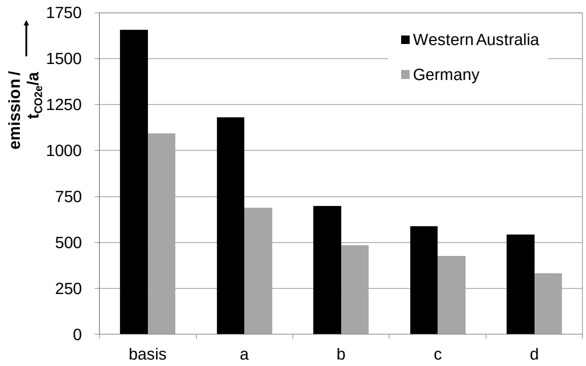

Fig. 4: Results for the emission of climate gases comparing Perth (WA) and Kassel (GER)

The usage of coolers instead of chillers leads to high reductions in CO_2e emissions in Central Europe. Positive results for the integration of a CHP arise from the inclusion of the displacement of centrally supplied electric power by cogeneration of electric energy. The German factory can use the winter release. During this time the CHP does not run because of the lack of a heat consumer. Nevertheless, the block heat and power plant runs about 5,500 h/a – which is necessary for economically feasible results. In Western Australia the CHP runs nearly all the time during production hours – a very good foundation for economic benefits.

Table 2 provides the numbers for the yearly greenhouse gases emitted and the demand of primary energy compared to the actual state of the considered areas.

Table 2: Primary energy and emission of carbon dioxide equivalents in Germany (GER) and Western Australia (WA) for the scenarios

	Primary energy reduction in %		**Emission reduction in %**	
	GER	**WA**	**GER**	**WA**
Current state	0	0	0	0
Optimisation a	36	30	37	29
Optimisation b	56	51	56	58
Optimisation c	58	51	61	64
Optimisation d	72	59*	69	67*

* assumption: same data for biomethane like in Germany

While the first step involving the winter release and the segregation of the mass flows pays for itself within a few weeks, the economic benefits for the following scenarios in both regions are more difficult to predict. Amortization periods depend on the individual prices and discount rates. Assuming that energy prices for natural gas and electric power are approximately at the same level for the medium sized producers in both regions, the gas-fired heating of the barrels are profitable in about 2.5 to 3.5 years. The results of the simulation show that the usage of natural gas in the CHP has only a small ecological and economical benefit. The state changes if the company switches to biomethane: The ecological data advance clearly. The benefit from the investment in a CHP strongly depends on government interest and promotion of energy efficiency and low carbon energy solutions. Western Australia is just starting to support green energy technologies. Germany already has a lawful basis for the operation. In a lot of cases the factories cooperate with an energy provider via contracting. The border for reasonable economical results for the CHP's heat is at about 3 €ct per kWh_{th}.

5 HEATING OF FACILITIES

Due to the fact that the average annual temperature in Western Australia is higher than in Germany, the need for heating of factory facilities differs considerably. This affects both production areas with and without internal thermal loads (machines) as well as administration buildings. Contact with Western Australian plastics producers has shown that they normally do not install heating systems, simply because it is not necessary. In one case, a heat recovery system was installed to use leaving air flow from the factory. German factories on the other hand do have to heat their facilities. Old heating systems with water-temperatures of 70 to 90 °C are common in this case.

This gives Western Australian factories an energetic advantage in this field. But there are smart solutions for German factories' management.

5.1 Potential for low temperature-systems

The first way energy smart solution to be discussed here is the investment in a system technology of low temperature-level. Three possibilities shall be mentioned:

- Heat recovery with used air out of production areas
- Heat from air compressors
- Machine heat (water cooling)

The highest potential can be found in the heat recovery out of the cooling of all the machines' parts excluding the mould. However, the cooling mass flow is slightly too cold. The solution is easy, and it brings a systemic advantage: Installing heat exchangers with a higher *UA*-value for higher thermal flows can help to lift up the temperature of both the hydraulic oil and of the cooling water. According to the information of a machine producer, this can be arranged without damaging the machine, and it has been observed in some Western Australian companies [10]. It is a reaction to the high air temperatures in the region. The water running off is only slightly warmer – but they can be decisive in low temperature-systems.

Another advantage is the rising degree of efficiency of the machine. Measurements show that the temperature of the oil influences the need for electric power $\rightarrow P = P(\vartheta_{\text{oil}})$.

Fig. 5 presents results for the correlation between the temperature of the hydraulic oil and the electric power.

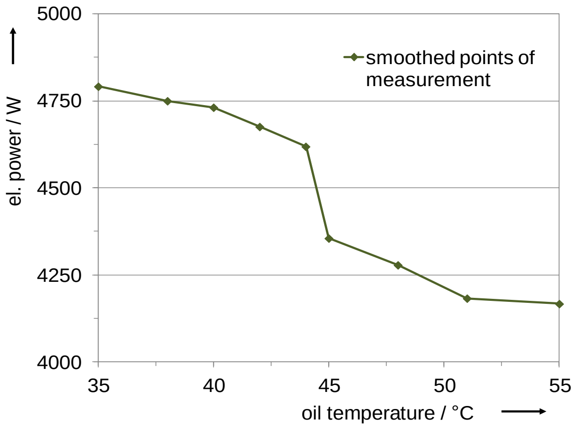

Fig. 5: Correlation between electric power and oil temperature at a moulding machine

The electric need of the production machine decreases for higher oil temperatures. The results presented are furthermore reviewed by measurements at a special testing unit at University of Kassel, for hydraulic systems.

5.2 Usage of hot water at a high temperature level

As shown in part 3, the heating of the barrels can be more energy efficient by using gas instead of electric power. Measurements at the testing unit have also proved the possibility to gain water temperatures at the boiling point. This level of temperature makes it valuable because it cannot be found normally in a factory's waste heat.

But the heat is of different value for companies in Germany than those in Western Australia. The first choice is to send it to an absorption chilling machine, because it needs a minimum temperature level of about 70 °C [14]. The crucial issue is: During winter time the chilling machines should be turned off leaving the task to the more efficient coolers. This affects German factories during about one third of the year. The climate of Western Australia allows this only very rarely. Consequently, the heat coming from the gas-fired unit can be used for nearly the whole year for the chillers. Assuming the German company thinks systemically, the valuable hot water flow of the gas-fired tempering unit is free for other processes. The heating demand for facilities and the winter relief from the coolers occur at the same time. Therefore, the heat can support the heating system for the facilities and prevent additional burning of fossil fuels. The following simulation results include thermal losses of the infrastructure to the production areas. Regarding the case of a project partner of the University of Kassel using an oil burner, the implementation would imply an extra reduction of about 65 MWh of primary energy, 17 t of CO_2e and 4,400 € per year.

6 SUMMARY

This simulation-based analysis suggests that there are a number of green energy initiatives that could be utilized by plastics-producing industries. The best solution differs according to the climate of the region and the particular policy goals (emission of climate gases, primary energy or energy costs). Factories in different regions face various tasks and conditions. If they consider the energy flows carefully and implement associated technologies there is ample potential for saving primary energy and costs as well as for reducing CO_2e emissions.

A whole system approach allows systemic solutions because it leads to the inclusion of all potential energy flows in order to reduce energetic losses. The results of the simulation reveal considerable potential in Germany and in Western Australia highlighting potential for low emission plastics production into the future.

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