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► To cite this version:

Bettina Muster-Slawitsch, Werner Weiss, Hans Schnitzer, Christoph Brunner. The green brewery concept - Energy efficiency and the use of renewable energy sources in breweries. Applied Thermal Engineering, 2011, 10.1016/j.applthermaleng.2011.03.033 . hal-00762974

HAL Id: hal-00762974

<https://hal.science/hal-00762974>

Submitted on 10 Dec 2012

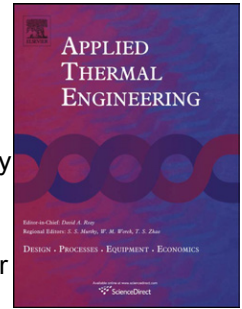
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Accepted Manuscript

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PII: S1359-4311(11)00165-7

DOI: [10.1016/j.applthermaleng.2011.03.033](https://doi.org/10.1016/j.applthermaleng.2011.03.033)

Reference: ATE 3488

To appear in: *Applied Thermal Engineering*

Received Date: 16 November 2010

Revised Date: 17 March 2011

Accepted Date: 22 March 2011

Please cite this article as: B. Muster-Slawitsch, W. Weiss, H. Schnitzer, C. Brunner. The green brewery concept - Energy efficiency and the use of renewable energy sources in breweries, *Applied Thermal Engineering* (2011), doi: 10.1016/j.applthermaleng.2011.03.033

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-The green brewery concept - Energy efficiency and the use of renewable energy sources in breweries

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KeyWords: food industry, energy efficiency, heat integration, solar process heat, renewable energy supply

The aim of the Green Brewery Concept is to demonstrate the potential for reducing thermal energy consumption in breweries, to substantially lower fossil CO₂ emissions and to develop an expert tool in order to provide a strategic approach to reach this reduction. Within the project “Green Brewery” 3 detailed case studies have been performed and a Green Brewery Concept has been developed. The project outcomes show that it is preferable to develop a tool instead of a simple guideline where a pathway to a CO₂ neutral thermal energy supply is shown for different circumstances. The methodology of the Green Brewery Concept includes detailed energy balancing, calculation of minimal thermal energy demand, process optimization, heat integration and finally the integration of renewable energy based on exergetic considerations.

For the studied breweries, one brewery with optimized heat recovery can potentially supply its thermal energy demand over own resources (excluding space heating). The energy produced from biogas from biogenic residues of breweries and waste water exceeds the remaining thermal process energy demand of 37 MJ/hl produced beer.

1 Introduction

The agro food industry encompasses a wide variety of processes and operations with a large supply chain. With the quest for sustainability and combat of climate change as major driving forces new developments in the food industry focus on multiple possibilities of introducing

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energy efficiency and the use of renewable resources as energy supply. For industry, the main possibilities for the reduction of GHGs will embrace 1) increased efficiency in energy conversion with an emphasis on cogeneration, 2) Process intensification and heat integration, 3) Zero-energy design for production halls and administrative buildings, 4) a shift in energy resources from fossil to renewable and 5) the use of industrial waste heat for general heating purposes outside the company (regional heating systems).

A number of studies so far have dealt with the optimization possibilities of food processing, applying process integration and the use of renewable energy sources. Process Integration for the food industry requires the consideration of batch processes. For breweries where rescheduling is a delicate issue due to the biological processes the adaptation or integration of storage tanks into the hot water management is a favorable option. Approaches for heat integration for batch processes including heat storage systems have been reported by several authors; however they are still not extensively studied [1-4]. The ideal choice of renewable energy resources for specific applications has been lately discussed by a number of researchers. Extensive reviews on methods and tools have recently been published by Banos et al. [5] and Collony et al. [6]. Total Site targeting methodology and its extension including varying supply and demand has been shown as a successful method for industrial and regional energy systems [7-11]. For the integration of solar heat a method has been established within the IEA SHC Task 33 Solar Heat for Industrial Processes. Its integration ideally takes place after heat integration of the production site [12, 13]. The vast potential for use of solar heat in industrial processes has been most recently reviewed by Mekhilef et al. [14].

For breweries much effort has been done lately in research and plant development to reduce the energy demand of the processes, visible through a large number of papers and publications. Typical energy demand figures, such as 24-54 MJ/hl beer for wort boiling, can be found in literature for different processes [15, 16]. However, in some breweries the real specific energy demand per production unit is unknown and improvements can therefore be hardly identified even if benchmarks are known.

This paper shows how a “Green Brewery Concept tool” was developed based on 3 case studies. The concept that aims to be used for a specific brewing site is an Excel based expert tool that guides breweries towards a production without fossil CO₂ emissions for covering the thermal energy demand. Although undergoing radical changes in production equipment is possible [16, 17], to a large extent similar technologies are used for brewing in different breweries. However, small technological differences and/or a varying ratio of brewing and packaging capacity influence the energy management of breweries already to a large extent.

Therefore, it is helpful to develop a tool instead of a simple guideline where a pathway to a CO₂ neutral thermal energy supply is shown for different circumstances and production capacities.

2 Methodology

The development of the Green Brewery Concept was based upon the experiences drawn from real plants. The concept was also tested using data from these medium-sized (production volume of 800,000-1,000,000 hectoliters/y) and small-sized (production volume of 20,000-50,000 hectoliters/y) companies.

In the case studies the thermal energy supply optimization has been studied for breweries via a methodological approach [18]. The optimization approach includes the development of target benchmarks via calculation of thermodynamic minimal energy demand, consideration of technology change, a bottom-up approach for heat integration via the pinch analysis and the integration of renewable energy based on the process temperatures and exergetic considerations rather than the existing utility system. The integration of renewable energy supply is considered subsequent to heat integration to ensure that no additional systems are installed if waste heat can serve the heating purpose.

The Green Brewery Concept tool follows the same steps in a simple form, as its aim is practical application by energy managers at the production site. The methodology applied in the case studies and the sections of the Green Brewery Concept are summarized in Figure 1.

Figure 1: Methodology for a Green Brewery

2.1 Data acquisition and energy balancing

In many industries the allocation of energy to processes is only known at the financial account level. A network of a few important measurements is necessary to develop optimization strategies and to have reliable benchmarks. Within the Green Brewery Concept the key parameters based on this network of measurements need to be entered. The calculation of the thermal energy demand is done on a process level based on the production data and technologies to allow for a detailed energy balance of the status quo in each compartment (brew house, fermentation and storage cellars, packaging and energy utilities (boiler, compressors)). In this way energy intensive steps and improvement targets can be promptly identified. The results of the energy balances are brought together in a list of benchmarks and compared with aim-targets.

Additional to the energy balance, the thermodynamic minimal energy demand for certain processes should be known as the ultimate target for energy demand reduction. In a first

approach this calculation needs to be based on the current technology; it can therefore be called the “minimal thermal energy demand per technology- $MEDT_{tech}$ ”. These values are usually known to plant designers, however not to plant operators. They can be calculated based on the basic thermodynamic principles, e.g. for a simple mash tun the calculation of one heating step simply is given by:

$$MEDT_{mash\ tun}, kJ / brew = V_{mashing\ liquor} * \rho_{mashing\ liquor} * c_{p\ mash\ing\ liquor} * (T_{final} - T_{mash\ in}) + m_{malt} * c_{p\ malt} * (T_{final} - T_{malt}) \quad (1)$$

The overall minimum thermal energy demand is given by the sum of all $MEDT_{tech}$ s within the brewery. It must be equal to the useful supply heat, which is given by the total net heat output from boilers, from combined heat and power (CHP) systems or from district heat, minus distribution losses and the loss due to process efficiency.

$$USH = \sum_{j=1}^k (m_j * H_{u,j}) * \eta_{conversion} + FET_{district\ heat} + FE_{CHP} * \eta_{thermal} \quad (2)$$

$$USH * \eta_{distribution} * \eta_{processes} = \sum_{i=1}^n MEDT_{tech,i} \quad (3)$$

Distribution losses can never be set to zero and the thermal process efficiency will be < 100%, however the knowledge of this ultimate benchmark for the technology in place can stimulate enhancements in efficiency.

2.2 Process optimization and heat integration

The methodology for reducing demand side savings is a two line approach. First, each unit operation is optimized via selection of the most efficient processing technology and ideal operation conditions. Second, process integration is done on the system level via the pinch analysis integrating all energy sinks and energy sources on the production site.

Optimization on unit operation level: From recent studies in Process Intensification it is known that the change of currently applied production technologies can increase process effectiveness and reduce energy requirements substantially [19]. $MEDT_{tech}$ calculations can be used to compare different technologies for the same process (e.g. wort boiling). New technologies also offer new opportunities for heat integration; however they might change the composite curves of breweries considerably. Thus, these changes need to be considered prior to final heat integration concepts. It has been shown that pinch analysis can also reveal operational changes for improved heat recovery [10], and an iterative optimization approach on unit operation level and system level is sensible.

The Green Brewery Concept includes a catalogue of energy efficient technologies and optimization measures for breweries. An overview of new technologies is provided with brief descriptions and references based on real data, several handbooks, books and articles.

Optimization on production site level: For thermal energy optimization on the system level, Pinch analysis has been applied for one case study taking into account all important thermal processes.

The presentation of the minimal heating and cooling demand in the pinch analysis of the case study is based on a time average approach [20] to allow for a quick analysis of the heat integration potential assuming storages can be implemented to overcome the mismatch in supply and demand. This approach is recommended for a first impression how much energy is available for possibly supplying the overall energy demand within a typical production week. For a development of a heat exchanger network (HEN) this approach is only valid as long as hot and cold streams that are matched to one heat exchanger do not have to overcome too large time variability.

After the presentation of the composite curves a heat exchanger network has been calculated for the case study based on a combinatorial design algorithm. The developed approach includes the parameters energy transfer (kWh/y), temperature difference between source and sink as exergy related parameter (ΔT) and power of the heat exchanger (kW) as the three main criteria. Economic targets are not included within the main decision criteria during theoretic HEN generation by the algorithm, as it has been shown that installation costs (piping, regulation etc. that cannot be quantified by an algorithm without detailed knowledge of the industry site map) are often more than 50% of the heat exchanger surface costs in the food industry. Economic evaluation is therefore done after the technical feasibility has been concluded.

The applied HEN algorithm can be either used on a time average approach or with consideration of time differences. In contrast to optimizing different networks in one time slice as has been shown by Kemp [20] and has been re-discussed by other authors [9, 2], one heat exchanger network is generated that overcomes time differences with possible storages. If process variability is large and time differences must not be neglected, necessary storage sizes (hot stream storages) are calculated by the algorithm. In that case the energy transfer over storage is considered in the proposed combinatorial approach of the HEN design. In case of the considered brewery A, available storage sizes ($>500 \text{ m}^3$) were large enough to justify the use of a time-average approach during theoretic HEN design.

The results of the HEN developed by the presented algorithm were taken as basis for applying practical constraints and developing a practical network on site, including available storages. Influencing factors for deviation of the theoretic HEN design by the algorithm and the practically applied HEN are piping distances, available space, necessary regulation effort, fouling of certain media, existing storages or company's willingness for major changes in thermal energy management.

The experiences of the pinch analysis are incorporated in the Green Brewery Concept. The concept calculates a generic list of heat sources and heat sinks based on the entered data of the brewery and states the potential for process integration for so far unused waste heat (see Table 1, list of heat sources). The potential is determined by available energy and temperature level. Based on these criteria, potential waste heat sources for heat integration embrace vapors from the boiling process, waste water from the KEG plant, de-superheating from the cooling compressors and waste heat from compressed air production. The largest waste heat sources within a brewery are the hot wort after boiling and vapors from wort boiling, already used for heat integration in breweries. The second largest waste heat source is condensation of the refrigerant of the cooling compressors; however this heat is released at quite low temperature and would require a heat pump to supply energy at a useful level. Due to the complexity of ideal HEN designs for the brewing process, heat integration networks and corresponding storage sizes are not pre-designed by the Green Brewery Concept but have been elaborated specifically for the case studies.

Table 1: List of heat sources and corresponding heat integration potential calculated for a specific brewing site in the Green Brewery Concept

2.3 Integration of renewable energy

The integration of renewable energy into an industrial energy system requires the consideration of availability of the renewable resource [11] as well as an exergy based approach to select the appropriate energy supply system. The methodology applied in this study is the analysis of the remaining energy demand after heat integration measures with annual load curves – well known to technicians on site from boiler design - on different temperature levels. This method has two advantages: 1) In this way the possibilities for integrating renewable energy (solar thermal, biogas, biomass, geothermal) can be identified depending on demand temperature and load changes without constraints of existing distribution systems. 2) Annual load profiles pose a good basis for designing future energy supply systems.

The choice of specific energy sources is done by evaluating their applicability to produce energy on different temperature levels, minimizing temperature dependant exergy loss. In the studies the choice of renewable energy sources was done based on temperature dependant load curves and the following procedure:

- 1) Ensure efficient process integration: demand side reduction and supply of heat demand by waste heat if possible (see 2.2)
- 2) Integrate low temperature energy supply for low temperature heat demand: For low temperature applications possible extended use of available district heat and heat from existing motor driven CHPs has been analyzed. Further, the integration of solar thermal energy has been considered. For the ideal integration of solar heat solar system simulations are required to identify the system efficiency and the achievable solar fraction under the given economic targets. Simulations applying the system simulation software T*SOL Expert 4.5 [21] were therefore elaborated for different scenarios.
- 3) Design a biomass based energy supply for the remaining heat demand at higher temperatures: For covering high temperature energy demand biomass or biogas boilers have been considered. Available resources, energy conversion potential, part load behaviour and integration possibilities into the existing energy system were key parameters influencing the choice between either one of them. The characteristic of breweries having spent grains as a large internal waste stream with huge energy conversion potential enables interesting waste to energy concepts. Batch fermentation tests were conducted to analyze the biogas production of residues from the brewing process (incl. spent grain).

Within the Green Brewery Concept the application potential for different energy sources (biogas, biomass, solar thermal, district heat, geothermal energy, heat pumps (low temperature waste heat)) is discussed for breweries under different framework conditions. Decision methods according to key figures (such as the technology applied in the brew house) were elaborated for different supply technologies based on the methodology discussed above. The required process temperatures in combination with the process load profile are the parameters that influence the choice of new supply equipments to the largest extent.

3 Results and Discussion

3.1 Description of the case studies

Figure 2 shows a general flowsheet of a brewing process. In brewing the thermal energy requirement is largely determined by the brew house. In the brewhouse mashing, wort

preheating and wort boiling constitute the most energy intensive steps. The generation of hot brew water is usually done over heat recovery from the hot wort that is cooled to cellar temperature. In packaging, the packaging technologies influence the heat requirements: In returnable bottle packaging the bottle washer and pasteurization are the most energy intensive processes. Pasteurization energy demand might range from 4-17 MJ/hl depending if flash or tunnel pasteurization is applied. In non-returnable bottle filling lines pasteurization is usually the highest energy consumer. In KEG packaging the cleaning of KEGs shows the largest hot water requirement and respectively a large waste water stream at significant temperature.

Figure 2: Simple brewing flowsheet

Three case studies were elaborated in the Green Brewery project. Brewery A and B are medium sized breweries with similar brew house technologies (infusion mashing, mechanical vapor compression (MVC)), while Brewery C is a small brewery applying decoction mashing and using a vapor condensation system to generate brew water from vapors released during wort boiling. Brewery A and C fill KEGs, brewery A and B fill returnable bottles, and brewery B has a non-returnable filling line as well.

3.2 Energy balance and minimal energy demand

The energy balance of 3 different breweries shows that the technology and operational parameters applied in the brew house, the brew volume, operating schedules and the ratio of brewing/packaging capacities influence the energy demand significantly. The results given in Figure 3 show a variation of specific useful supply heat for thermal process energy (excluding space heating requirements) between 43.6 and 104.5 MJ/hl. Final thermal energy requirements are in the range of 60 MJ/hl for breweries A and B and show that benchmarks reported in literature [22-24], such as 85-120 MJ/hl are often higher than real best practice.

Figure 3: Minimal thermal energy demand $MEDT_{tech}$ versus useful supply heat for processes

The current thermal energy input for processes already taking into account conversion losses of the boiler house (USH) is compared with the minimal thermal energy demand for the technology in place ($MEDT_{tech}$) which is calculated for each process based on its specific requirements (e.g. temperature, heating rates, evaporation rates) and the existing technology. As the current study was focused on thermal energy optimization, electrical energy requirements were only included if they were important for the thermal energy duties (e.g. mechanical vapor compression). $MEDT_{tech}$ is usually highest for the brewhouse, in the range between 20-25 MJ/hl depending on production capacities. Similar values are reported in the

literature [22]. All breweries show a deviation from the overall $MEDT_{tech}$ for all production units to $USH_{processes}$ in the range of 28% to 37% highlighting the losses that appear in distribution systems and due to process inefficiencies. Especially in small breweries these losses are due to the batch processes and non-continuous operation (Brewery C), in larger breweries supplied with steam open steam condensate systems contribute largely to losses (Brewery A and B).

3.3 Pinch analysis

Pinch Analysis has been done in greatest detail for brewery A. Figure 4 shows the hot and cold composite curve for brewery A including brew house and packaging with a minimum allowed temperature difference of 5 K and averaged power during process operation hours. Visibly a large amount of waste heat can be recovered. In breweries a large part of this potential is already realised via the wort cooler that preheats incoming fresh brewing water. Next to this standard measure the most common heat recovery options in modern brew houses include mechanical and thermal vapor compression and vapor condensation in connection with a heat storage to preheat the wort before boiling [16, 25] .

Figure 4: Hot and cold composite curve for brewery A (brew house and packaging), shown with average power during process operation times

Based on the pinch analysis a heat exchanger network was developed for brewery A on a thermodynamic ideal approach applying the developed HEN design algorithm (see chapter 2.2.). The theoretic network generated in a time average approach during a 5 day production week shows the selection of heat exchangers by thermodynamic criteria. Several ΔT_{min} were applied. As the aim of the theoretic heat integration network was to show an ideal network that uses high effective heat exchangers, the result of a network with ΔT_{min} of 5 K is presented. For breweries a ΔT_{min} of 5 K is technically possible with high effective heat exchangers, as all streams except flue gas and spent grain are liquids and existing heat exchangers (e.g. well designed flash pasteurizers) in breweries are already operated with very low ΔT_{min} . Additionally hot water produced over the hot wort or vapor condensation is often directly used in processes and heat transfer losses do only occur in storages. In general the algorithm highlights the use of hot waste heat streams for direct process integration. Brewing water for mashing and lautering should only be heated to target temperatures. The developed theoretic heat exchanger network for a brewery with mechanical vapor compression suggests (Figure 4):

1. The generation of brewing water over the wort cooler at highest possible temperature, e.g. 94°C and the subsequent use of brewing water for preheating the incoming wort and the mash tun;

After preheating of the wort, the heating of the mash tun is thermodynamically suggested. This cools the brew water (660hl/brew) below 75°C. In that case the brew water can no longer fully supply the lautering process that requires 75°C (310hl/brew). However, for brewery A the heating of preheated water to lautering temperature would be less energy intensive than the mashing process. It needs to be highlighted that this subsequent use of brew water for wort preheating and mashing is a theoretic outcome of the design algorithm that did not undergo practical verification. Time variations between brews need to be considered in detail, whether intelligent storage management could guarantee stable operating conditions.

Generally heating of low temperature processes, such as mashing, with low temperature heat sources is exergetically important, however different issues need to be tackled to realize it for retrofits. It is known that heating the mash tun requires certain heating rates and a very low ΔT between heat source and sink can therefore hardly be realized. Pumping the mash can also pose a problem because broken husks might affect the following lautering process negatively. If lauter tuns are installed internal plate heat exchangers are a possible solution for heating the mash tun. Heating the mash tun with hot water from vapor condenser has already been suggested by Tokos et al. [26].

2. the use of the cooled brewing water (66°C) for lautering and mashing liquor;
3. Additional generation of hot brewing water from other heat sources, such as heat recovery from hot spent grain or steam condensate cooling.
4. Generation of water for CIP, packaging plants and service water from hot waste water, vapor condensation from boiling start-ups, vapor condensate recovery, heat recovery from hot spent grain and waste heat from cooling compressors.

Heating requirements of process/service water should be limited to bringing preheated water to lauter liquor (75°C) and CIP (80°C) target temperature. In this way 3 temperature levels would be available on site. A simplified grid diagram representing the thermodynamically suggested HEN is shown in Figure 5, corresponding heat capacity flowrates are given in Table 2. As the theoretic pinch analysis has been done on a time average approach, power of actual heat exchangers deviate from the outcome of the theoretic HEN algorithm.

Figure 5: Thermodynamically ideal heat integration network for brewery A with MVC based on the pinch analysis (time-average approach): use of hot brew water for wort preheating and for heating the mash tun

Table 2: Heat capacity flowrates for streams used in theoretic HEN design

This heat integration network was adapted in cooperation with the energy and brewing managers to fit best to the current installations (see Figure 6 and Table 4). Wort preheating in this considered brewery A is already implemented via local district heat at very competitive price, therefore theoretically suggested use of hot brew water for wort preheating is not feasible. The practical measures for heat integration for the same brewery include:

- Generation of brewing water over the wort cooler at 85°C and use for mashing and lautering (as existent and proven sensible by the theoretic approach);
- Elevate existing process water tank to 85°C (currently 70°C) via integration of vapor condensation from boiling startups, optimized vapor condensate recovery, integration of heat from subcooling of steam condensate and integration of waste water from brew house CIP (the outcome of the theoretic approach for generation of water for CIP, packaging plants and service water was adapted to the existing process water tank on site);
- Use water from elevated process water tank for packaging;
- Installation of additional tank for waste water recovery from KEG plant for service water and heating requirements (because of the distance from the KEG plant to the process water tank, a local heat recovery would be preferable over the integration of the waste heat into the process water tank).

The measures reduce thermal energy requirements by 25%. Economic evaluation was done for the first three measures and showed that the measures had a payback period of less than 1.5 years (see Table 3).

Table 2: Estimated payback periods and savings

Figure 6: Practical heat integration network for brewery A with MVC incl. nominal power of new heat exchangers

Table 4: Heat capacity flowrates for design of practical HEN

In Brewery B, that shows a very similar hot and cold composite curves due to its operational similarity to brewery A, a CHP system is installed and remaining heat recovery options were focused on integrating waste heat of cooling compressors for preheating boiler feed water and as well as the optimization of the wort cooler. Brewery C was shown to be too small in its production capacity to make any of the suggested heat recovery options economically viable.

3.4 Solar process heat integration

Based on the load curves of remaining heat demand the integration of solar heat was considered. The potential for solar heat application in breweries is high, as all processes except conventional wort boiling run below 100°C and flat plate or vacuum tube collectors meet these temperature requirements well. For countries with high direct solar radiation the supply of high temperature processes with solar heat over concentrating systems is as well possible. In principle hot water distribution systems can be recommended for breweries. Distribution losses can be minimized and solar thermal heat can be well integrated into the processes.

According to the pinch theory solar process heat should be integrated above the pinch if energy requirements below pinch can be supplied by heat recovery. Using solar heat for process water generation is only sensible if heat recovery measures cannot meet the hot process water demand. For the considered breweries it could theoretically be shown that careful use of hot water and an intelligent heat integration network make heating requirements for hot water unnecessary. However, it was also shown that high temperatures available from wort cooling and the vapor condensation (if installed) should be used primarily for process integration and water heating requirements should be met by low temperature heat sources. If a low temperature heat source is difficult to tap because of practical hindrances, solar heat could become a viable choice for hot water generation. Looking at the pinch analysis, the solar thermal potential is highest for the packaging area and the mashing process. The integration of hot water based heat exchangers outside existing bottle washing plants makes solar process heat also possible for retrofits.

The monthly load curves of the remaining energy demand for brewery A show that after heat integration energy is required at >72°C (see Figure 7). The mashing process requires a lot of energy to heat the mash liquor from 60-75°C (shown in the monthly load curve of 75°C). Other processes at 72-85°C embrace the packaging plants. In brewery A packaging is already supplied by low temperature heat coming from the local district heat. Solar process heat was therefore considered for CIP in packaging. 500 m² vacuum tube collectors could supply 165 MWh/y or 21% on the total CIP energy demand respectively (see Figure 8). In future the supply of the mashing process will be considered. Similar challenges as reported earlier for hot water heated mash tuns will have to be tackled. Large steam driven vessels will require a technological change of the mashing process to integrate solar heat.

Figure 7: Load curves of remaining thermal energy demand by temperature levels

Figure 8: T-Sol simulation of solar process heat integration in the hot water circuit for CIP in packaging

3.5 Biogas and biomass integration

The batch fermentation tests showed that for a brewery with a production capacity of 900,000 hl beer the energy yield from biogas out of spent grain can be as high as 36 MJ/hl. Biogas from waste water can additionally increase this figure. The combustion of spent grain with 40% humidity on the other hand can produce 46.5 MJ/hl (basis 15,000 t/y spent grain and 900,000 hl produced beer). Here an advanced drying technology is necessary, as fresh spent grain with 80% humidity has a heating value of 24.7 MJ/hl. Within the Green Brewery Concept, the combination of real process data from the specific brewery and key data known from studies allow the calculation of the potential of energy generation from different biogenic residues. A nomogram showing the potential energy generation from spent grain fermentation based on the results from batch fermentation tests is shown in Figure 9. Starting from the diagram above the potential of energy production over spent grain fermentation can be quickly estimated depending on the production capacity.

For the considered breweries A and B it could be shown that biogas integration is technoeconomical the most sensible option due to the existing framework conditions: 1) The boiler needs to cover peak loads efficiently and respond easily to load changes. 2) The infrastructure is partly available (biogas from waste water is already integrated in the gas boiler in brewery A). 3) Cooperation possibilities with existing biogas plants, treatment systems and the local gas net are possible.

For brewery A with a remaining energy demand of 37 MJ/hl after implementation of the optimization measures biogas from spent grain and waste water can potentially fully supply the brewery with energy (see Figure 10). Space heating in winter is not included in this figure as it is supplied by district heat from a wood power plant. Gas savings (basis 2007) amount to 1,200,000 Nm³ gas and CO₂ savings are 2,670 t/y (based on GEMIS database). For brewery B similar savings could be achieved via spent grain fermentation. For brewery C on the other hand being located in a small rural community, biomass supply would be the more sensible alternative for reaching minimum fossil CO₂ emissions, together with integration of local district heat.

Figure 9: Example of nomogram for potential thermal heat generation from renewable sources – biogas production from spent grain

Figure 10: Energy flow diagram for future energy supply in brewery A

4 Conclusions

The Green Brewery Concept has been developed as a tool to reduce emissions and to give guidance for decisive actions in order to improve thermal energy efficiency. It is aimed as a living tool that can be extended and updated according to the best engineering practices. The application of the methodology has proven that a high potential exists for breweries to lower thermal energy requirements with process optimization, heat integration and the integration of renewable energy. The detailed work in thermal energy management in close cooperation with energy managers on site has shown to contribute to continuous energy savings in breweries by elevating the sensibility of workers and managers.

The calculation of minimal energy demand of processes has proven to be efficient in evaluating distribution and process efficiencies and stimulating corresponding enhancements. The integration of such calculation within the Green Brewery concept offers energy managers of breweries the opportunity to evaluate the thermal energy efficiency on site simply by entering their key process data.

The hot water management of a brewery is the key factor for integrating waste heat or new energy supply technologies. It is highly influenced by production capacities (brewing vs. packaging) and the technology as well as operational parameters applied in the brew house [24], as well as by the type of packaging (KEG, bottle etc). The evaluation of present hot water management within the Green Brewery Concept as well as the comparison of available heat in energy sources with necessary energy demand give important information on improvement potentials.

The result of the pinch analysis for breweries shows that heat integration over direct storages need to be integrated in an intelligent way, as often hot water that is generated from waste heat can later be directly applied in processes. The heat available at high temperatures needs to be re-used at similar temperatures and the exergy should not be destroyed by mixing with cold water. An example of such an intelligent “energy swing” is the use of the hot brewing water for preheating the wort and the consequent use as brew water. Practical networks deviate from theoretic design because local conditions, as existing storage tanks, must be considered. Ideal storage sizing and management based on heat integration and renewable energy integration is seen as an important target for future simulation studies. This has been shown similarly for indirect storage tanks in other industries [3]. Also, existing storage tanks should be included in HEN design algorithms.

For renewable energy integration the importance of exergetic considerations of the energy supply system has been highlighted. Solar process heat has proven to have a large potential for breweries, especially in packaging and on a long term perspective for mashing.

The application of the Green Brewery methodology has shown that the remaining thermal energy demand that can be reached in the considered breweries with 1,000,000 hl production capacity is as low as 37 MJ/hl for brewery A (excluding space heating requirements). The possibilities for reaching this target depend on the production cycles and on the balance between hot water demand in brewing and packaging. It could be shown that even for brewery A with existing vapor recovery systems (mechanical vapor compression) 25% of the energy can additionally be recovered by reusing waste heat from vapors at boiling start-ups, waste water from brew house CIP, subcooling of steam condensate and waste water from the KEG plant. The necessary measures show a payback period of less than 1.5 years. Brewery A with optimized heat recovery and comparable production capacities in brewing and packaging can therefore potentially supply its thermal energy demand with own resources (excluding space heating). The energy produced with biogas from biogenic residues of breweries and waste water exceeds the remaining thermal energy demand of 37 MJ/hl. Integration of biogas was the favorite alternative over biomass for the considered breweries A and B due to the existing infrastructure and cooperation possibilities with existing biogas plants, treatment systems and the local gas net. Plant design and economic evaluation will be further elaborated.

Overall, the project „Green Brewery“ has shown a saving potential of over 5,000 t/y fossil CO₂ emissions from thermal energy supply for the 3 breweries that were closely considered. For brewery A it could be shown that the total fossil gas demand can be substituted saving 2,760 t/y fossil CO₂ emissions.

5 Outlook

Ongoing activities will focus on an improved calculation of minimal energy demand, which needs to include electric energy and the consideration of exergy efficiency. Exergy analysis for one African brewery has lately been reported [23]. Ultimately a comprehensive analysis of different technologies is needed to identify the technology with the best energy and exergy efficiency. This minimal energy demand and exergy loss can then be used as a true benchmark for the process itself – $MED_{process}$. Additionally new (intensified) technologies need to be evaluated on their minimal energy demand. As technological change influences the thermal energy demand and hot water management of breweries significantly, process models for evaluating the best suitable technologies and operating conditions for an ideal heat integrated production site will be necessary. Effects of technological change on the overall energy balance, on heat integration possibilities and on the integration possibilities of

renewable energy need to be analyzed. HEN design algorithms need to be extended to allow consideration of existing storage tanks and integration of several heat sources into central storage systems.

6 Acknowledgment

We especially thank the Brau Union Österreich as project leader and all project partners (Joanneum Research, Steirische Gas Wärme GmbH, Fischer Maschinen- und Apparatebau AG and Energie Service Friesenbichler) for the fruitful collaboration. We appreciate the financial support of the funding agency Österreichische Forschungsförderungs-gesellschaft mbH (FFG).

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Figure Captions

Figure 1: Methodology for a Green Brewery

Figure 2: Simple brewing flowsheet

Figure 3: Minimal thermal energy demand MEDTtech versus useful supply heat for processes

Figure 4: Hot and cold composite curve for brewery A (brew house and packaging), shown with average power during process operation times

Figure 5: Thermodynamically ideal heat integration network for brewery A with MVC based on the pinch analysis (time-average approach): use of hot brew water for wort preheating and for heating the mash tun

Figure 6: Practical heat integration network for brewery A with MVC incl. nominal power of new heat exchangers

Figure 7: Load curves of remaining thermal energy demand by temperature levels

Figure 8: T-Sol simulation of solar process heat integration in the hot water circuit for CIP in packaging

Figure 9: Example of nomogram for potential thermal heat generation from renewable sources – biogas production from spent grain

Figure 10: Energy flow diagram for future energy supply in brewery A

Nomenclature			
$MEDT_{tech}$	Thermodynamic minimal thermal energy demand per technology, kJ	FE_{CHP}	Final energy input into CHP, kJ
V	Volume, m ³ /brew	USH	Useful supply heat (including space heating), kJ
ρ	Density, kg/m ³	USH _{processes}	Useful supply heat for processes, kJ
c_p	Heat capacity, kJ/(kg*K)	m	Mass of fuel input, kg
T_{final}	Final process temperature, K	H_u	Lower heating value of fuel, kJ/kg
$T_{malt/mash}$	Start temperature in mashing process, K	$\eta_{conversion}$	Conversion efficiency in the boiler house
m_{malt}	Mass of malt input in mashing, kg/brew	$FET_{districtheat}$	Final energy input for thermal use from district heating, kJ
$\eta_{thermal}$	Thermal efficiency of CHP system	$i \dots n$	Indices for each process
$\eta_{distribution}$	Distribution efficiency	$j \dots k$	Indices for each fuel
$\eta_{processes}$	Overall process efficiency	GHG	Greenhouse gas emissions
IEA SHC	International Energy Agency, Solar Heating and Cooling Programme	CIP	Cleaning in place
CHP	Combined heat and power plant	KEG	Metal beer barrel

Waste sources**Potential for heat recovery**

Please state which heat sources are already included to heat recovery

(yes = already included)

		kWh/week	°C	HIGH	MEDIUM	LOW
waste heat contained in spent grain	no	26,315	75	x		
vapour losses at boiling start-ups	no	13,196	100.3	x		
vapour condensation	yes	97,890	100			
vapour condensate recovery	yes	14,759	95			
wort cooling	yes	182,139	95			
Waste water brew house CIP	no	9,164	70	x		
waste water bottle washer	no	10,475	30			x
waste water tunnel pasteurizer	no	not installed				
waste water CIP packaging	no	3,259	70		x	
waste water bottle rinser	no	385	70			x
waste water crate washer	no	1,862	40			x
waste water KEG outside cleaning	no	663	30			x
waste water KEG washing	no	21,672	70	x		
waste water CIP KEG plant	no	436	75			x
vapours from KEG steaming	no	2,854	70		x	
waste heat cooling compressors (de-superheating)	no	17,676	110	x		
waste heat cooling compressors (condensation)	no	92,626	30			x
waste heat pressurized air compressors	no	16,657	70	x		
boiler flue gas	no	15,519	130	x		
other waste heat (e.g. from CHP) if applicable	no	not applicable				

Heat capacity flowrates for streams matched in theoretic

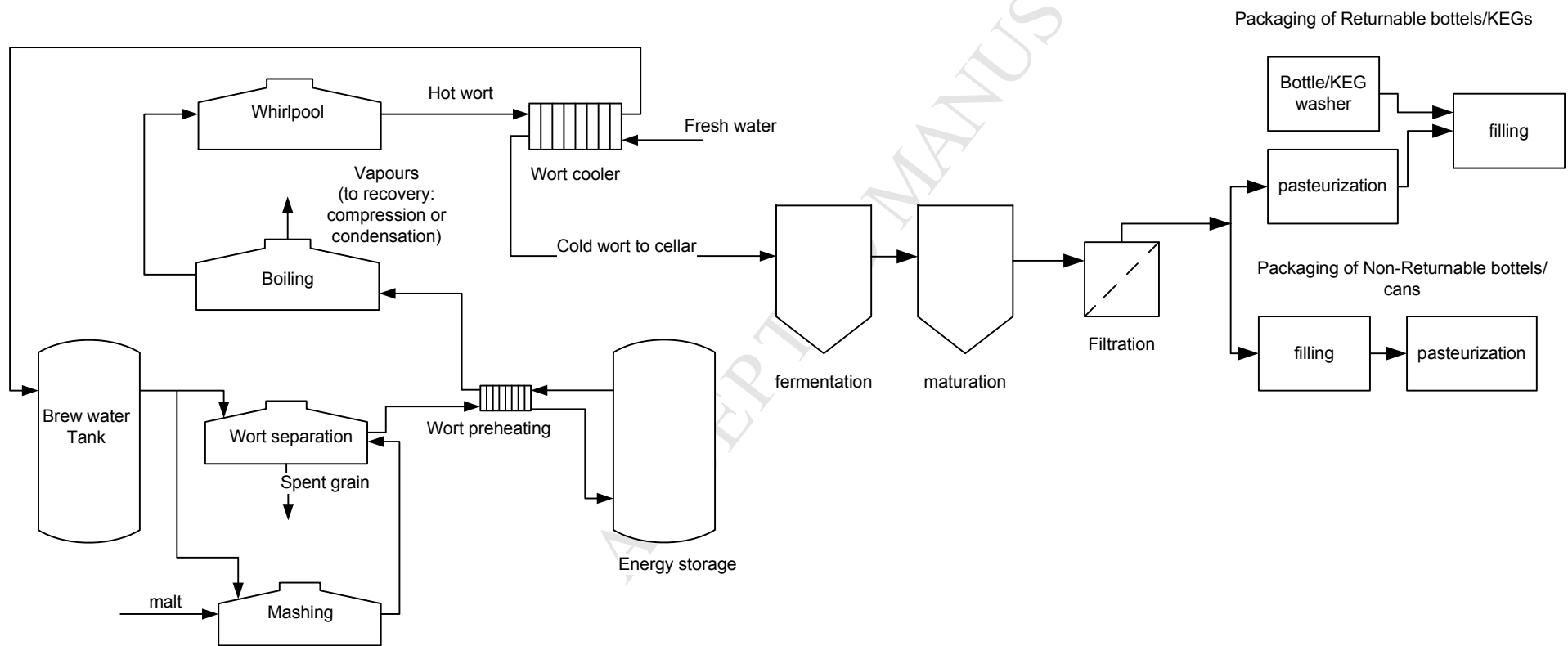
HEN algorithm	Heat Capacity Flowrate C_p [kW/K]
Hot water generated over wort cooling	22.4
Wort preheating	23.24
Mashing	22.16
Brew water for rinses (Lautering)	10.52
Brew water for mashing	13.92
Process water for packaging & CIP	3.4
Boiler Feed Water	1.23
Vapour condensate cooling	1.36
Hot water generated from condensate cooling	1.16
Waste water from CIP	0.76
Hot water contained in spent grains	3.53
Heat recovery from cooling compressors	1.52
Hot water generated from Vapours from boiling start-ups	1.16
Flue gas from boiler	1.3

Heat integration for process water generation	Possible energy savings kWh/week	Savings €/a	Payback years
Waste water brew house CIP	8,380	16,760	1.2
Vapours from boiling start-ups	10,821	20,850	0.9
Subcooling of steam condensate	11,173	23,826	0.8

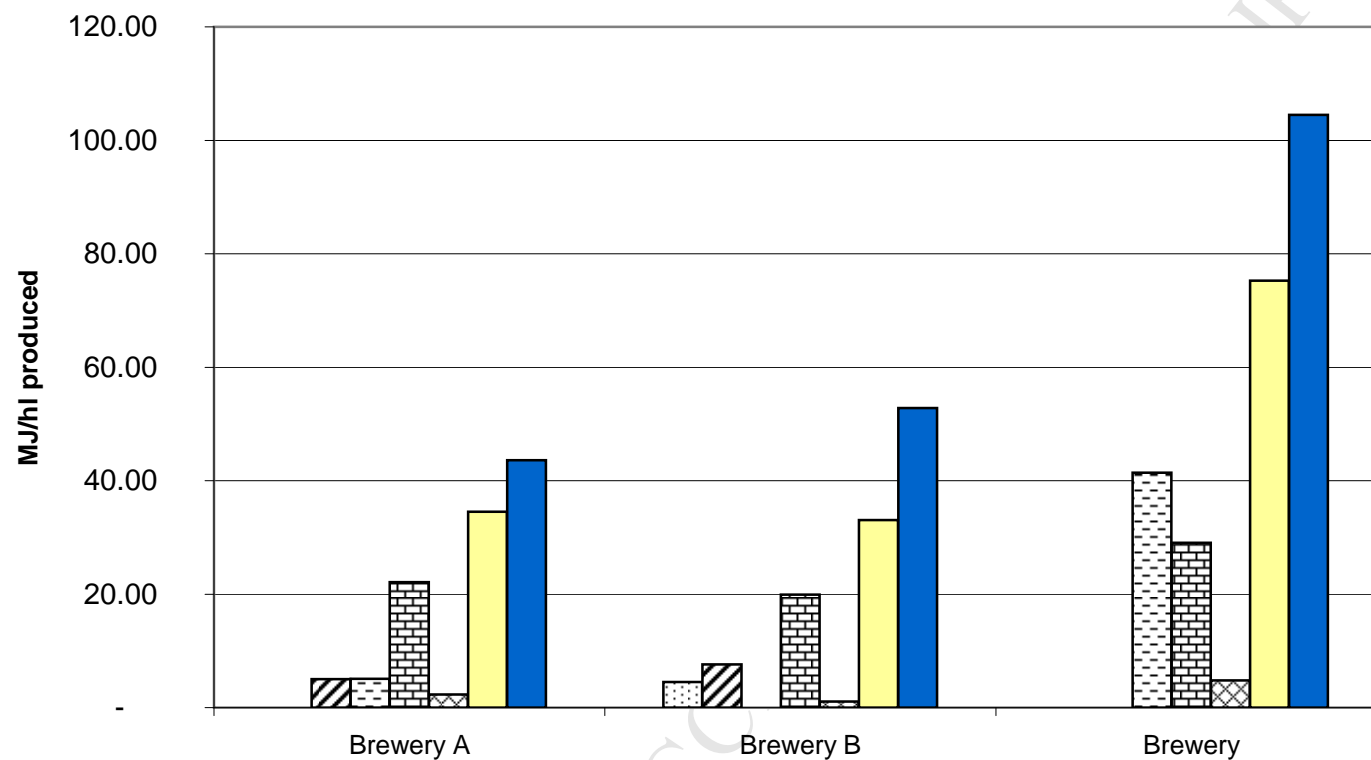
Heat capacity flowrates for design of practical HEN	Heat Capacity flowrate C_p [kW/K]
Vapour condensate cooling	4.7
Steam condensate cooling	13.9
Waste water from CIP	81.4
Vapours from boiling start-ups	3.1

ACCEPTED MANUSCRIPT

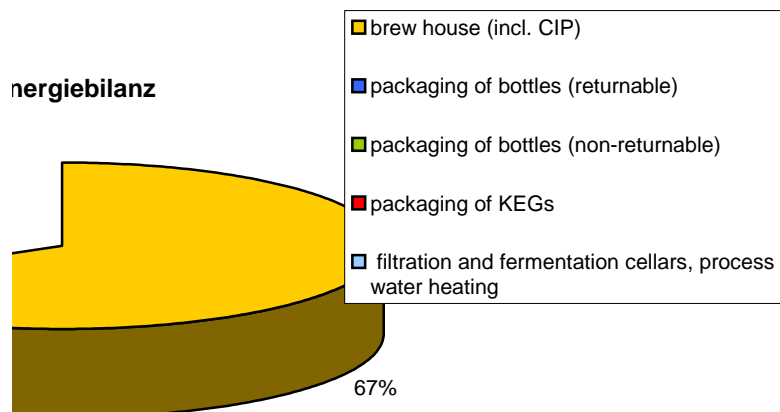
Methodology for a Green Brewery			
Steps	Methods	Results	Corresponding section in the Green Brewery Concept
Data acquisition	<ul style="list-style-type: none"> - On-Site visits - Network of important measurements 	Thermal energy streams (load profiles of energy demand and availability) & existing storages	Section 1.1 Checkpoints – entry of key figures
Energy demand analysis <ul style="list-style-type: none"> - Energy balancing - Comparison of actual demand figures vs. benchmarks - Identification of process efficiencies, distribution losses 	<ul style="list-style-type: none"> - Thermal energy balance - Benchmarking - Calculation of thermodynamic minimum energy demand 	<ul style="list-style-type: none"> - Thermal energy balance - Identification of areas with high optimization potential 	Section 1.1.a – 1.1.e Thermal energy balance of each production area Section 1.2. Checkpoint Analysis – Benchmarking and visualisation of process inefficiencies Section 1.3. Overall thermal energy balance, visualisation of distribution losses
Energy demand reduction <ul style="list-style-type: none"> - Process optimization/ technology change - Heat integration 	<ul style="list-style-type: none"> - Cleaner Production measures - Technology evaluation - Pinch Analysis incl. storage considerations - Annual load curves of remaining thermal energy demand by temperature levels 	<ul style="list-style-type: none"> - Identification of savings due to technology change - Heat Exchanger Network - Exergetic analysis of remaining energy demand profile 	Section 2.1 – 2.4. Catalogue of energy efficient technologies & optimization measures (brew house, packaging, boiler house, cooling.) Section 1.4. Generic list of heat sources and sinks & visualisation of heat integration potential
Integration of renewable energy	<ul style="list-style-type: none"> - Techno-economic evaluation for implementation of renewable energy resources - Specific design tools (T-Sol) for renewable energy implementation 	Concepts for integration of renewable energy resources	Section 3.1. – 3.7. Description, potential & applicability of renewable energy integration (solar thermal, biogas, biomass, heat pumps, photovoltaic, district heat, geothermal energy)

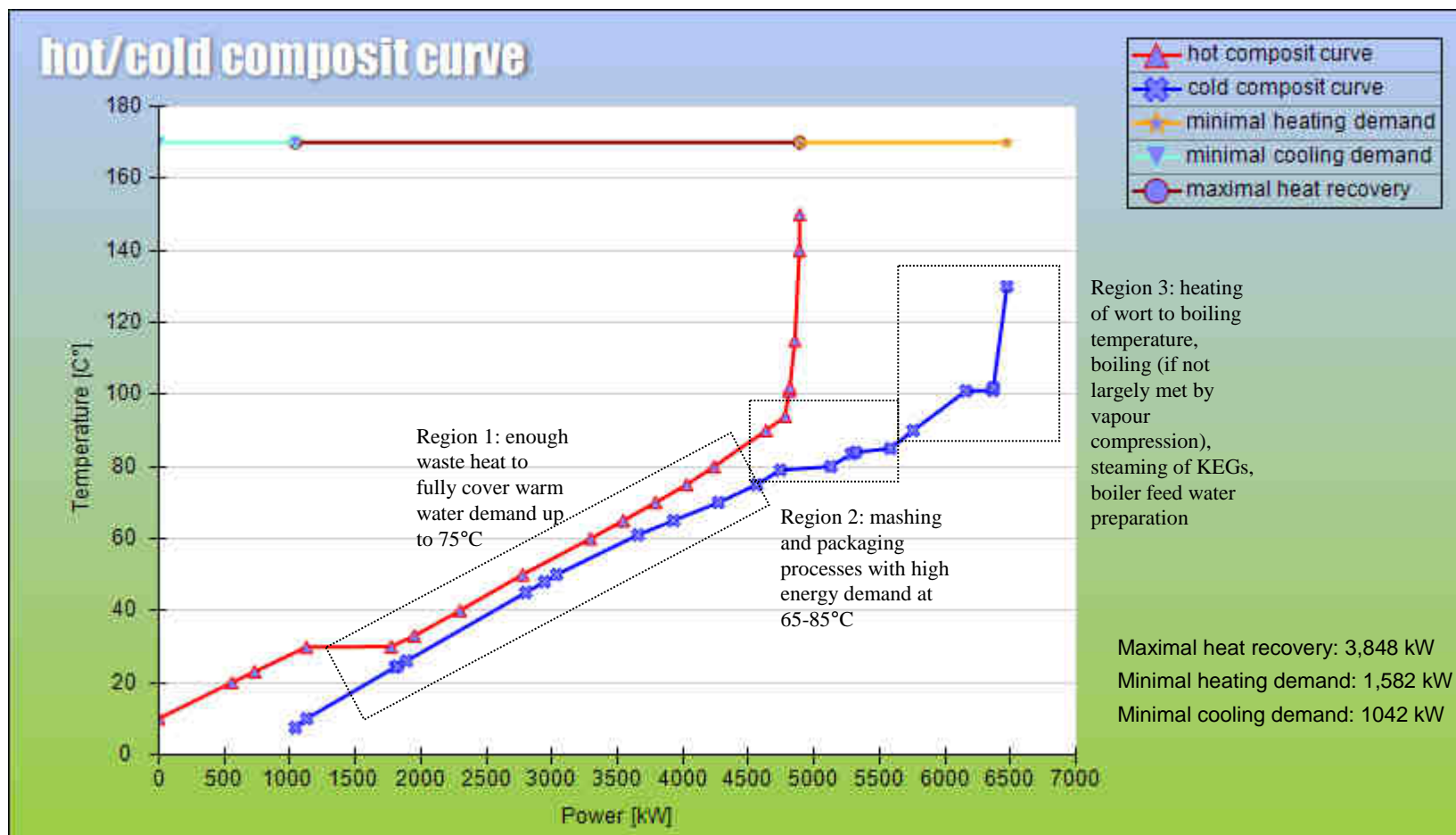


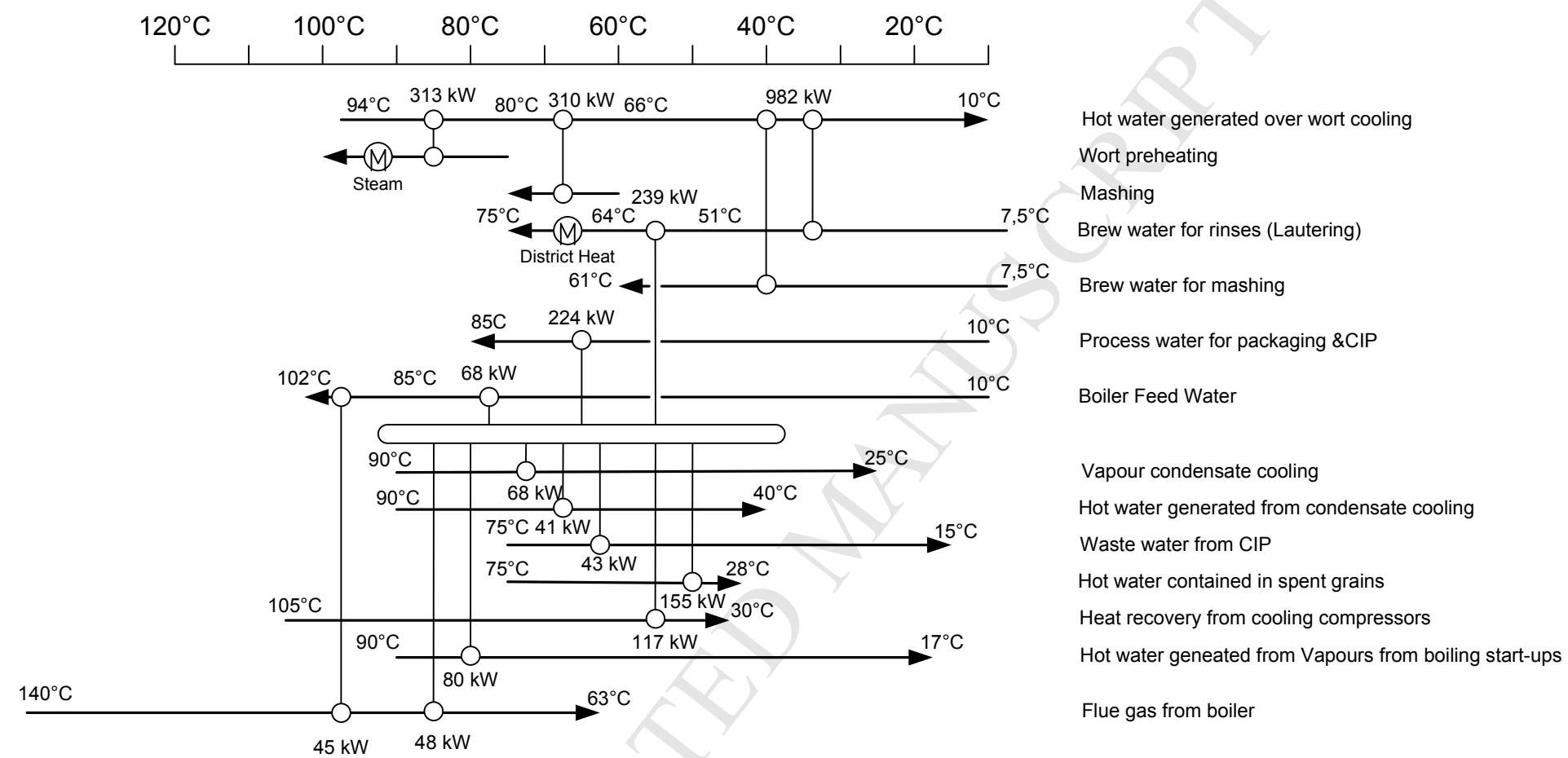
Minimal thermal energy requirement
 (based on current production parameters and water use)
vs. useful supply heat for processes

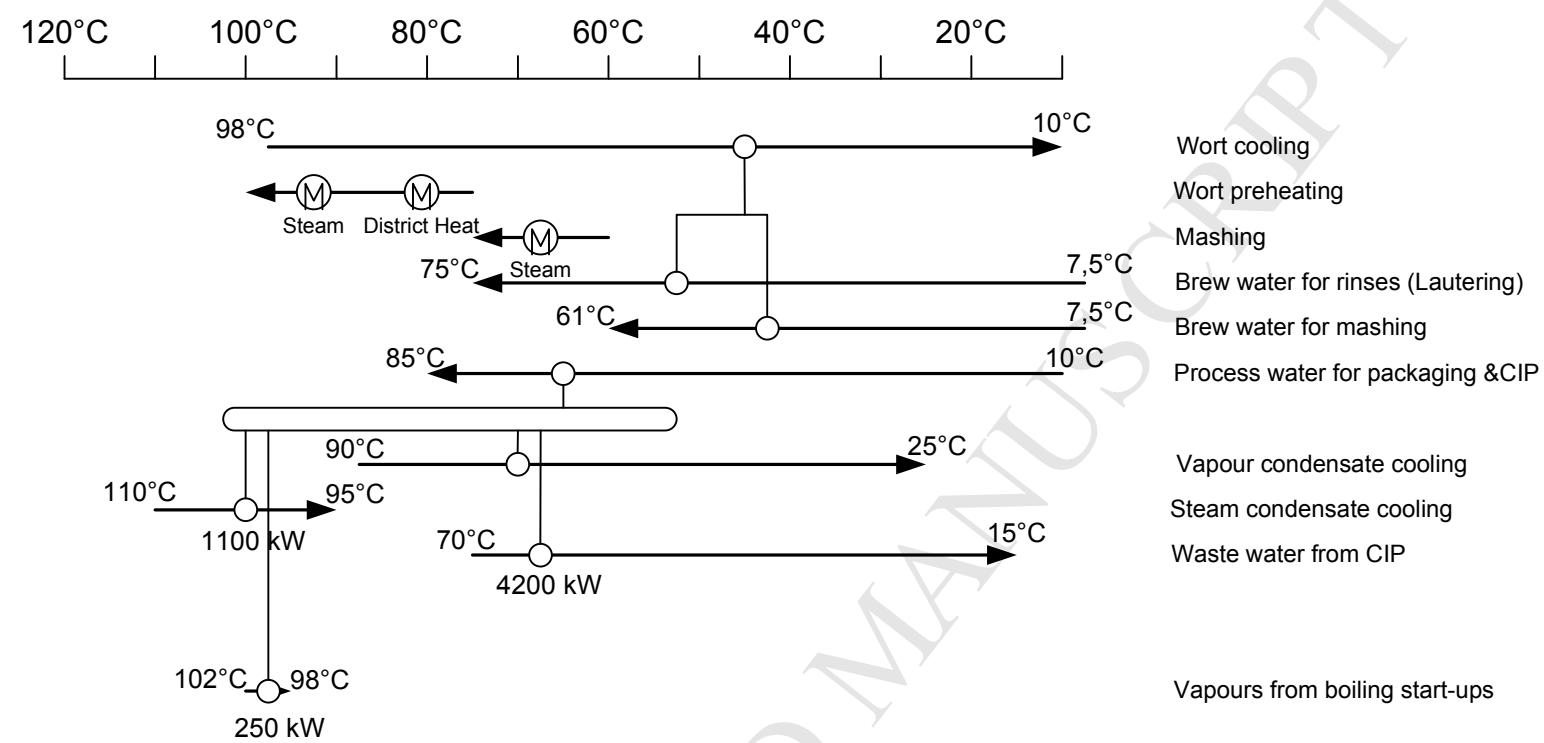


- | | |
|--|---------------------------------------|
| ▨ packaging of bottles (non-returnable) | ▨ packaging of bottles (returnable) |
| ▨ packaging of KEGs | ▨ brew house (incl. CIP) |
| ▨ filtration and fermentation cellars, process water heating | ▨ Total minimal thermal energy demand |
| ▨ useful supply heat for processes | |

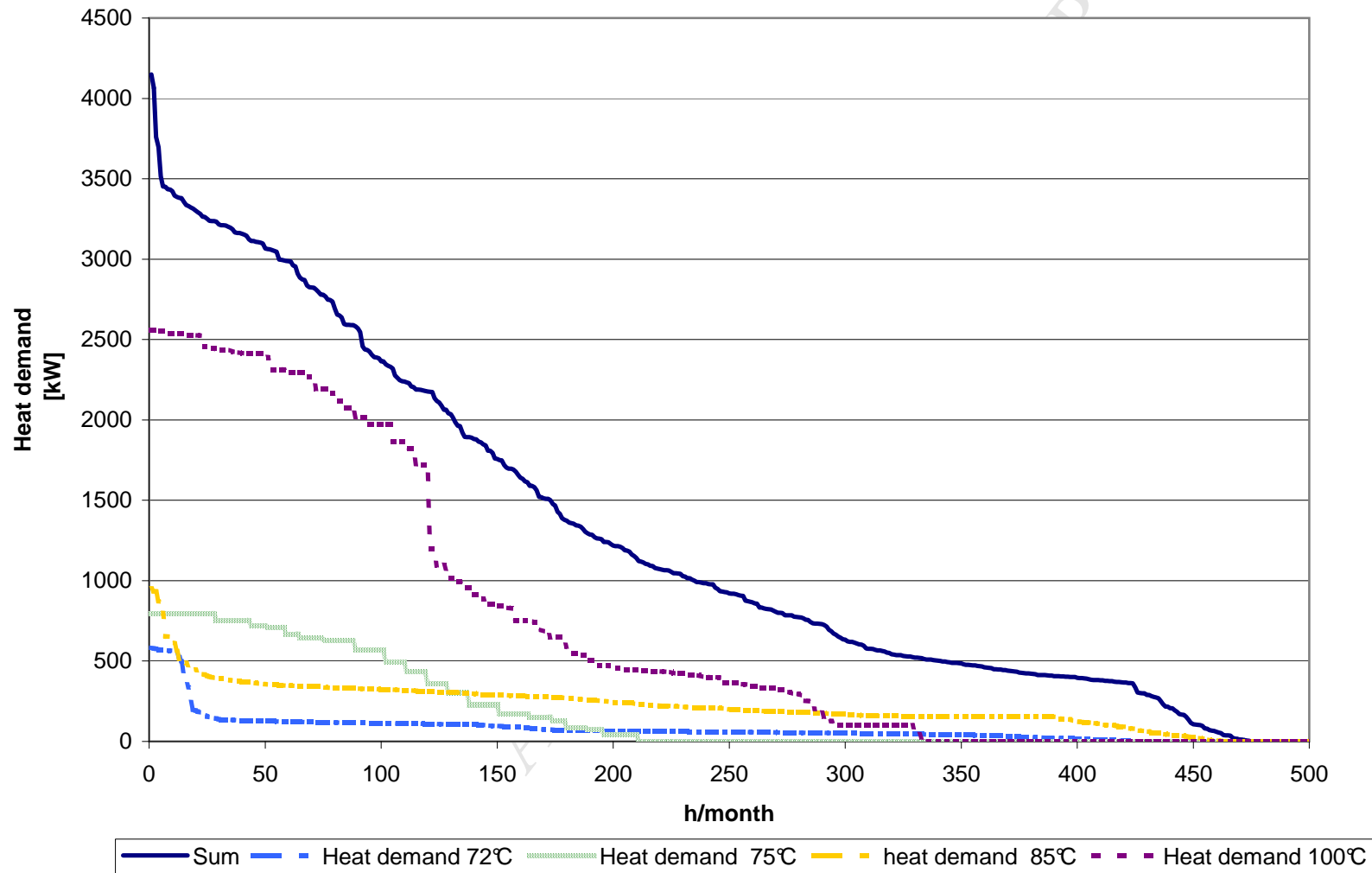


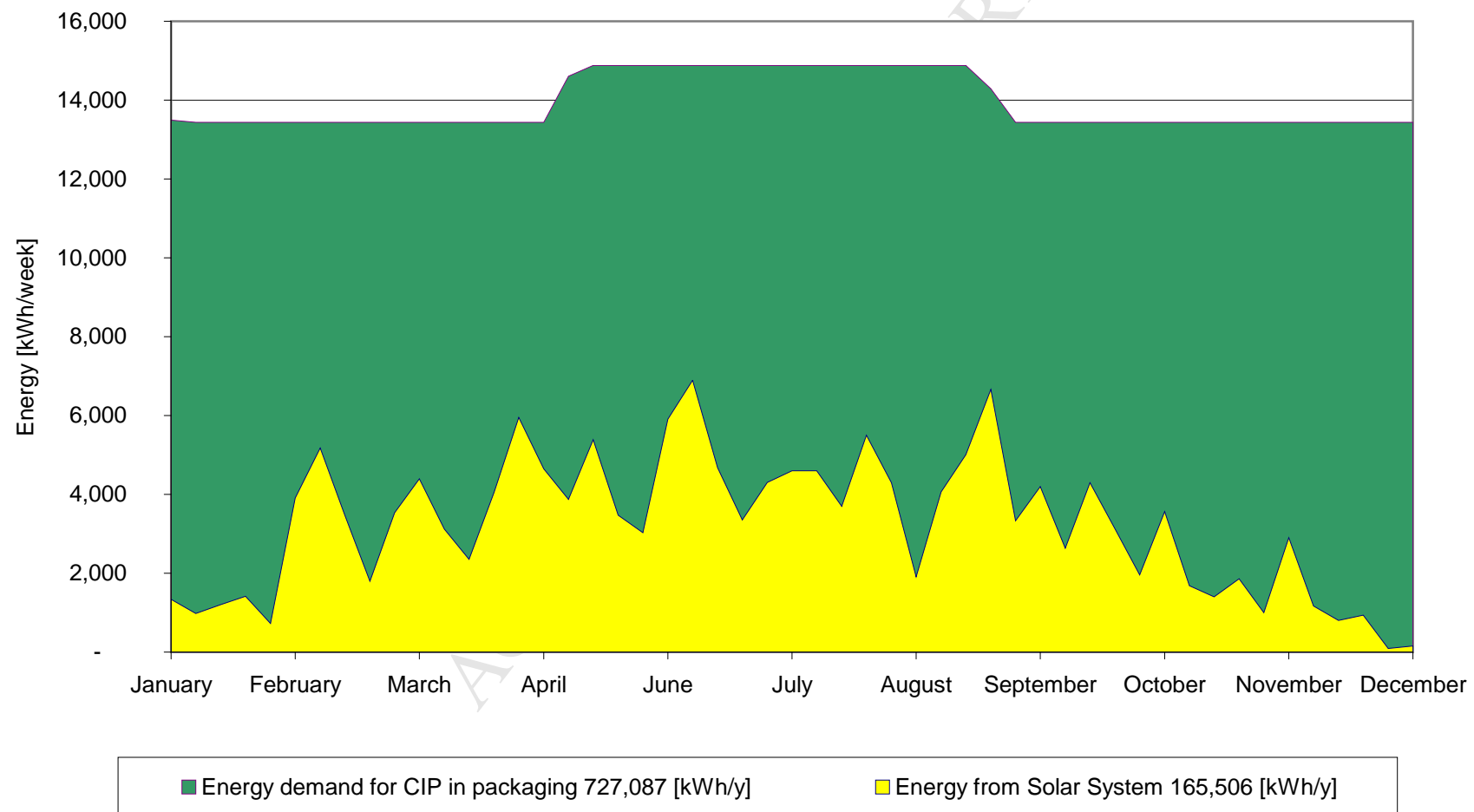






Monthly heat demand - load curve after heat integration
hourly average values





brewing capacity, hl/y	mass of humid spent grain, tons/y		
	17 kg spent grain/hl	18 kg spent grain/hl	19 kg spent grain/hl
50,000	850	900	950
100,000	1,700	1,800	1,900
200,000	3,400	3,600	3,800
400,000	6,800	7,200	7,600
600,000	10,200	10,800	11,400
800,000	13,600	14,400	15,200
1,000,000	17,000	18,000	19,000
1,200,000	20,400	21,600	22,800
1,400,000	23,800	25,200	26,600
1,600,000	27,200	28,800	30,400
1,800,000	30,600	32,400	34,200
2,000,000	34,000	36,000	38,000
2,200,000	37,400	39,600	41,800
2,400,000	40,800	43,200	45,600

mass of humid spent grain, ton	biogas production potential, MWh/y		
	methane content 40%	methane content 55%	methane content 70%
500	180,000	247,500	315,000
1,000	360,000	495,000	630,000
5,000	1,800,000	2,475,000	3,150,000
10,000	3,600,000	4,950,000	6,300,000
15,000	5,400,000	7,425,000	9,450,000
20,000	7,200,000	9,900,000	12,600,000
25,000	9,000,000	12,375,000	15,750,000
30,000	10,800,000	14,850,000	18,900,000
35,000	12,600,000	17,325,000	22,050,000
40,000	14,400,000	19,800,000	25,200,000
45,000	16,200,000	22,275,000	28,350,000
50,000	18,000,000	24,750,000	31,500,000
55,000	19,800,000	27,225,000	34,650,000
60,000	21,600,000	29,700,000	37,800,000

biogas production potential, M	heat production potential, MWh/y		
	$\eta_{\text{conversion}} = 0,7$	$\eta_{\text{conversion}} = 0,8$	$\eta_{\text{conversion}} = 0,9$
100,000	70,000	80,000	90,000
500,000	350,000	400,000	450,000
1,000,000	700,000	800,000	900,000
5,000,000	3,500,000	4,000,000	4,500,000
10,000,000	7,000,000	8,000,000	9,000,000
15,000,000	10,500,000	12,000,000	13,500,000
20,000,000	14,000,000	16,000,000	18,000,000
25,000,000	17,500,000	20,000,000	22,500,000
30,000,000	21,000,000	24,000,000	27,000,000
35,000,000	24,500,000	28,000,000	31,500,000

20 kg spent grain/hl

1,000
2,000
4,000
8,000
12,000
16,000
20,000
24,000
28,000
32,000
36,000
40,000
44,000
48,000

6

Bsp
1,000,000.00 hl/y
19,000.00 tons spent grain/y
11,970,000.00 MWh/a
43,092,000.00 MJ/a
with eff = 0,85
36,628,200.00 MJ/a
36.6282 MJ/hl

