Hardware in the loop evaluation of a hybrid heating system for increased energy efficiency and management

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Keywords
energy efficient technologies, heat supply, combined heat and power (CHP), load management, energy management, hybrid, heating systems, simulation, waste heat recovery, pasteurization, hardware in the loop evaluation

Abstract
This study presents the tests of a hybrid heating prototype, designed for retrofitting thermal treatment plants like pasteurization, to use hot water and steam in controlled ratios. In the food industry, steam with a temperature above 140 °C usually supplies the thermal production processes. The majority of processes require temperatures below 100 °C and could be supplied more efficiently by cogeneration, heat recovery or heat pumps. These low temperature heat sources can only be combined with the rigid steam system if the demand structure is changed to a hybrid use of hot water below 100 °C and steam. The hybrid heating system (H^2S) increases the energy efficiency by integrating the highest possible amount of low temperature heat and responds to sudden changes in the supply structure, like demand response strategies on intermittent renewable energies and the changing availability of hot water and steam.

The technical implementation is realised by a hydraulic interconnection of heat exchangers and valves. A smart algorithm controls the integration of hot water and steam into the thermal process. For reasons of food safety and product quality defined process temperatures have to be met. Prerequisite for functional verification on a laboratory scale is a simulation of the process heat demand and potential of hot water during the entire production cycle. The load profiles and relevant process parameters are passed in real time to a hardware-in-the loop (HIL) test-bed and returned to the simulation respectively.

Two scenarios, hot water integration from heat pump and demand response management with a gas engine CHP and an electrical steam generator, were evaluated and the functionality of the H^2S was proved. Up to 78 % of the final energy demand can be reduced by the H^2S based implementation of a heat pump. The control response of the system, even with fluctuating hot water potential and temperature, met the requirements of the dairy industry.

Introduction
While most industries are busy improving their energy efficiency, the share of renewable energies will continue to rise. The prediction of energy production from wind farms and solar PV power stations can only be precise to a certain degree. Demand response (DR) technologies are necessary to stabilize the frequency and avoid load shedding of power from wind and solar PV. Net providers are dependent on flexible companies able to adjust their electricity consumption in order to balance positive and negative demands. This gives a monetary motivation for companies changing between fossil based heat supply and electrical heating systems. In terms of power-to-heat technologies heat pumps are used for the efficient integration of waste heat, but also electric steam generators are increasingly important for DR management and supply of high temperature heat. Expanding renewables is one option towards a cleaner industrial production but in the meantime the efficient use of energy still has to be increased.

According to the German Energy Agency (dena), the German industrial sector uses 57 % of total industrial energy for process heat applications, giving rise to potential economic viable energy savings of 30 TWh/y (dena 2011). To increase the efficiency of thermal energy supply three main areas are important: modernization of heat utilities, heat recovery from processes, and the efficient use of rejected heat from utilities, e.g. CHP, chillers, and condensing economizers. All of these technologies and methods need sinks of low temperature heat (LTH), i.e. hot water below 100 °C. This is not applicable for all industries, i.e. industries with high Pinch Temperatures (>100 °C) such as the steel and iron industry, where LTH is produced in excess (Johansson and Söderström 2014). The food and beverage industry is one of the sectors, where most of the process heat can be provided by LTH. Schmitt (2014) found a low temperature heat potential of 2.5 TWh/y in Germany, which represents 58 % of the sector's heat demand. Even though there is a high potential, the integration of LTH is still low. One problem is the lack of knowledge in industry for the usage of heat flows from excess heat. Another problem is that there is not enough political motivation for its use (Broberg Viklund 2015). Further, the investment costs and the heat supply based on steam are disabling LTH technologies. In the food and beverage industry, gas fired steam boilers are the state-of-the-art and in most cases the only supplier of process heat. Using high temperature heat (HTH) from steam allows serving all processes with one boiler, leading to low specific investment costs. An efficient supply of heat needs a LTH grid for the integration of waste heat streams, hot water from CHP, heat pumps (HP) or solar thermal. For the cost-effective implementation of an LTH-grid as many LTH sinks, with high load and reasonable operating time, as possible have to be located and integrated.

Typical thermal unit operations in the food and beverage industry are pasteurization, sterilization, cooking, cleaning, evaporating and drying. Besides cleaning, pasteurization is an obligatory thermal process in this sector. It is used for products, ranging from fruit juices, beer, dairy products, sauces, pickles to fish and meat products (Silva and Gibbs 2009). Especially in the dairy and fruit juice industry, pasteurization has a high impact on the total energy demand. Waheed et al. (2008) found that pasteurization is the most energy intensive unit operation in the processing of orange juice. Its importance in the dairy industry is reported by Ramirez et al. (2006), calling it the most common thermal process. Pasteurization is generally a low temperature process (60–100 °C) with different heating temperature and holding time combinations, which assure the reduction of viable pathogens to a secure level. Continuous pasteurization of milk in plate heat exchangers (PHE) for example is conducted at 72–74 °C with a holding time of 15–30 s (Sun 2012). Indirect steam heaters with a pressurized hot water (HW) loop as an intermediate heat carrier are commonly used to avoid fouling (Simpson 2009), which otherwise would occur due to high contact temperatures. Fouling causes losses in product quality, increases pressure drops, and decreases heat transfer rates (Saravacos and Kostaropoulos 2016). Industrial pasteurization plants are usually a combination of the actual pasteurization zone, a preheating and a cooling zone as shown in Figure 1. The steam supply is regulated by a pressure reducing valve (PRV).

Pasteurization is a LTH sink with a high load, long running time and a wide spread application in the food processing industry. Also, it is already equipped with a hot water loop providing a good integration point for LTH. For processes like pasteurization, an argument against the use of hot water is the sensitivity of this process. Recoverable LTH sources are often considered as unreliable and therefore not suitable to provide these processes without a backup by HTH. Therefore, hybrid heating systems supplied by hot water from waste heat streams and efficient utilities (e.g. heat pumps), backed by a secure heat source like steam from a natural gas boiler are necessary. In case of maintaining CHP and HP redundancy is essential. For reasons of dynamic loads and a fluctuating temperature of the waste heat source the HP needs additional steam supply.

The aim of this paper is to show that a pasteurization plant can be effectively retrofitted (or designed) to a Hybrid Heating System for the smart use of low and high temperature heat sources. A prototype has been designed, built and equipped with a control algorithm to handle changing supply strategies and fluctuating hot water temperatures. It has been experimentally tested on its functionality and reliability with regard to maintaining process target temperatures.

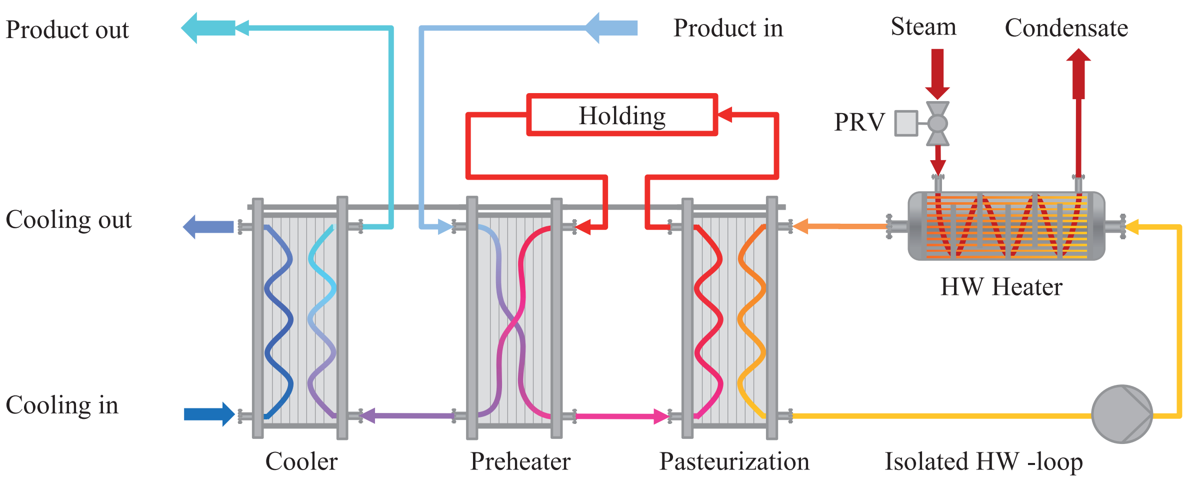

Figure 1. Continuous thermal treatment plant for pasteurization.

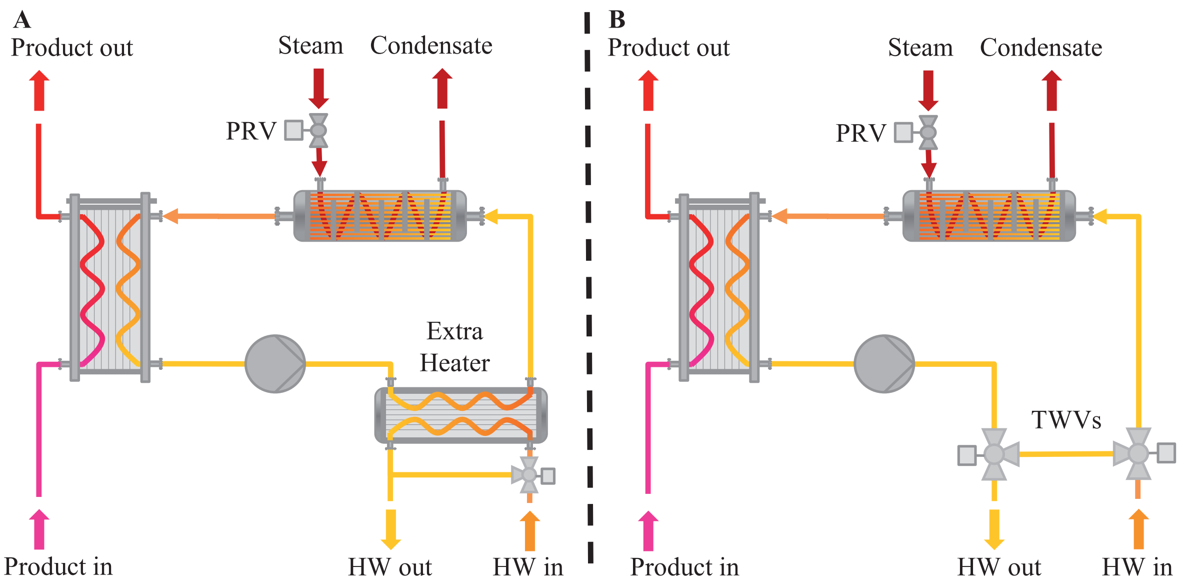

Figure 2. Systems for HW-Integration into pasteurization with hot water loop. System A) return flow boost with PHE; system B) HW-integration with three-way valves.

Theory on Hybrid Heating Concept and Control

The Hybrid Heating System (H^2S) (Schumm et al. 2015) consists of two parts: A hydraulic system able to switch between hot water as the LTH and steam as HTH source and an algorithm managing the control of the product temperature regarding the available heat resources.

The origin of the hybrid-heating concept was the retrofitting of indirect heaters to use the installed infrastructure for the economic integration of LTH. Usually, hot water is directly integrated in the process flow using an extra heat exchanger as a preheater, which is favored considering process integration and thermodynamic optimization. But heat exchangers contacting food are more expensive than for utility systems. PHEs used for the food processing use gaskets as the sealant because the plates must be regularly checked and, potentially, exchanged. For utility heating brazed plate heat exchangers (BHE) can be used. BHE have a better ratio of used material to heat exchange area hence have lower investment costs. Product contact plates have also higher specification on the alloys resulting in higher material prizes. Besides the lower costs on equipment the HW-loop integration has further advantages compared to a LTH integration in the product line. The installation can be done without influencing the production process, has a better hygienic design due to the lower exchange surface and no extra maintenance costs. Therefore the existing indirect HW-loop may be used as the integration point for LTH. This solution for the integration of LTH into the process of pasteurization was also investigated by B.KWK Bundesverband (2011) for a CHP and Muster et al. (2015) for solar thermal integration. Both their concepts (Figure 2A) use an extra heat exchanger in the return flow of the hot water loop as an integration point for LTH. The solution presented in this paper is the integration via two three-way valves (TWV) (Figure 2B). HW-sources for Figure 2B include direct integration using low-grade heat from CHP, HP, and solar thermal units and indirect integration via PHEs for heat recovery from hot process streams. Keeping the steam heat exchanger as a backup and/or final heat supplier is common to both concepts.

Both options for the HW-loop integrations are quite similar in terms of costs. For System A, an extra heat exchanger for utility contact and a control valve are necessary. System B needs two three-way valves; this can be more expensive for small duties and cheaper for big plants compared to the extra heat exchanger. The HW-integration with three-way valves was chosen for the prototype because of higher utility duty substitution due to options of direct integration. It is also smaller in size and has therefore a benefit for retrofitting. In general, both systems serve the idea of a hybrid heating system which allows to heat the product by two different sources.

The investigated system setup (System B) allows providing heat for the process in all different shares of LTH and HTH. A constantly calculated comparison between the acceptable LTH integration and the capacities of LTH and HTH on the supply side identifies the safest way to efficiently reach the set temperature of the product ($T_{P,P,o,set}$). Available capacities of the LTH- and the HTH-sources or a surplus of steam decide how the H^2S can and should be supplied. These constraints are taken into account for calculating the contribution of each heat source to deliver the requested duty ($\dot{Q}_P$) to heat up the product.

$$\dot{Q}_P = \dot{m}_P \cdot c_{p,P} \cdot (T_{P,P,o,set} - T_{P,P,i}) \qquad (1)$$

If the HW flow temperature ($T_{H,H,o}$) is high enough to safely reach $T_{P,P,o,set}$, no steam utility is necessary. But if under the same conditions a surplus of steam is generated, e.g. as a result of DR, steam will replace hot water up to the desired value. In all other cases HW from LTH sources is preferred. To express the portions of LTH and HTH, an auxiliary quantity, called the energy recipe (ER), is defined as the ratio of LTH duty to product duty (Equation 2). Since the sum of LTH and HTH should always equal $\dot{Q}_P$ only one ratio is necessary to define the shares of all heat flows:

$$ER = \frac{\dot{Q}_{LTH}}{\dot{Q}_P} \quad (2)$$

The ER is calculated once on a general basis (external ER – ER_{ex}) and individually (internal ER – ER_{in}) for each Hybrid Heater. The ER_{ex} is calculated based on a possible surplus and unused capacities considering the available resources and the current demand of LTH and HTH. The ER_{in} calculates the maximum amount of hot water that can be integrated at a certain HW temperature taking the production recipe into account. Both values are compared against each other taking the lower one as the new set value (ER_{set}). This guarantees, that LTH is only used if it is available, the HW temperature is high enough to be integrated and no surplus of HTH should preferably be used. Figure 3 shows how a set of multiple Hybrid-Heaters can be arranged to achieve holistic intelligence for optimized energy consumption. The exchange between the external and the individual heaters is bilateral. $ER_{in,i}$ and $\dot{Q}_{P,i}$ are sent back to the ER_{ex} where the individual loads are added and the ER_{in} values are weighted (Equation 3), to summarize the current allocation of LTH and HTH.

$$ER_{total} = \frac{\sum_{i=1}^{N} \dot{Q}_{P,i} ER_{in,i}}{\sum_{i=1}^{N} \dot{Q}_{P,i}} \quad (3)$$

This information is necessary, to calculate the potential to shift loads with the H^2S, in determining the ER_{ex} which is then sent back and compared with the $ER_{in,i}$.

The H^2S-control can be classified into four control strategies (CS 1–4) shown and explained in Figure 4. Depending on the circumstances an ER_{set} for each H^2S unit is calculated which defines the matching control strategy.

The ER_{set} is used to determine which actuator, the PRV or the TWVs, is active and which one is passive. Generally both actuators can and must be used to adjust the product temperature with a control loop. To avoid complications with mutual disturbing controls, only one of them is activated while the other is fixed to a calculated value. The ER can vary from 0 (pure HTH) to 100 % (LTH only). The parameter ER_{23} is used to define the transition from LTH-control to HTH-control. In between the boundaries a mixed supply can either be controlled by the PRV or the TWVs while the other one contributes its calculated value. Set positions for the passive actuator are provided online by characteristic curves for PRV and TWVs, matching the ER_{set}. The algorithm for ER_{ex} and ER_{in} and the stepwise alignment to ER_{set} are coded in the same programmable logic control (PLC) that controls the process itself.

Materials and Method

The development of the control algorithm and the building of a testing facility were parts of the research project (Schumm and Schlosser 2016) .The setup was tested with the help from MATLAB Simulink based simulation-tools developed within the projects (Philipp and Schlosser 2016) and (Philipp and Schumm 2014). In section one of this chapter the hydraulic instruments and devices for heat supply and transfer are presented. The second part deals with its validation method, showing the interconnection between the simulation models and the PLC via an Open Platform Communication (OPC) connection. The last part presents the scenarios used to demonstrate the operational functionality and reliability.

TESTING FACILITY SETUP

For the experimental testing, heat is supplied by an electric steam generator and a HW-tank with integrated immersion heaters. Saturated steam is produced at 4 bar from the electric steam generator, which is reduced to 1 bar in the PRV and transferred to the HW in a BHE (HW-Heater). Both systems, the HW-heater and the HW-tank, can provide HW-temperatures up to 100 °C. The settings of the two TWVs (TWV_1 and TWV_2) determine if the HW is either circulated in the hot water loop, also passing through the HW-tank or mixing parts of the return flow from the P-Heater with the flow from the HW-tank. The product (P) is pumped between a cooler, a buffer storage and the PHE for pasteurization (P-Heater). The product pump is an eccentric screw pump type with variable speed drive. The pilot plant of the H^2S, illustrated in Figure 5, is designed to supply and transfer 40 kW at each stage.

At all relevant locations temperature sensors, pressure transducers and flow meters are installed and connected to the PLC where the process is observed and actuators like pumps and valves are controlled. To analyze the actual formulation of the

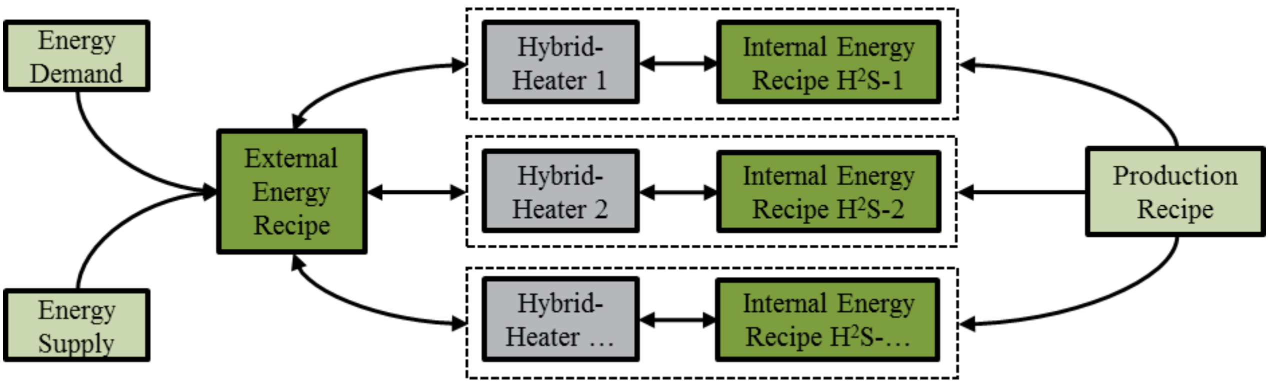

Figure 3. Concept of multiple Hybrid-Heaters for the optimization of the supply structure.

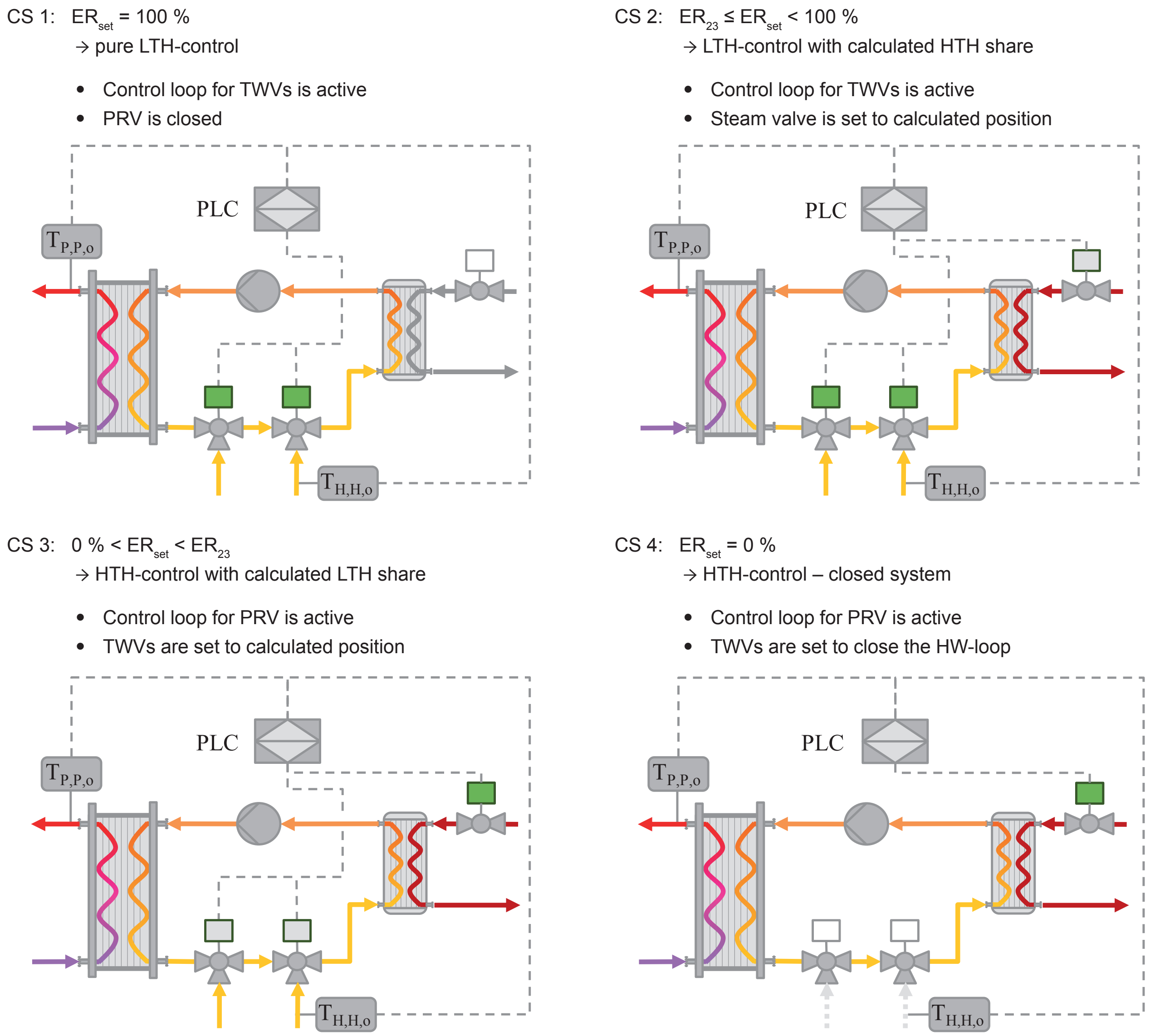

Figure 4. Variations in H²S-control mechanisms. Doted lines show active information flows between sensors, actuators and the PLC.

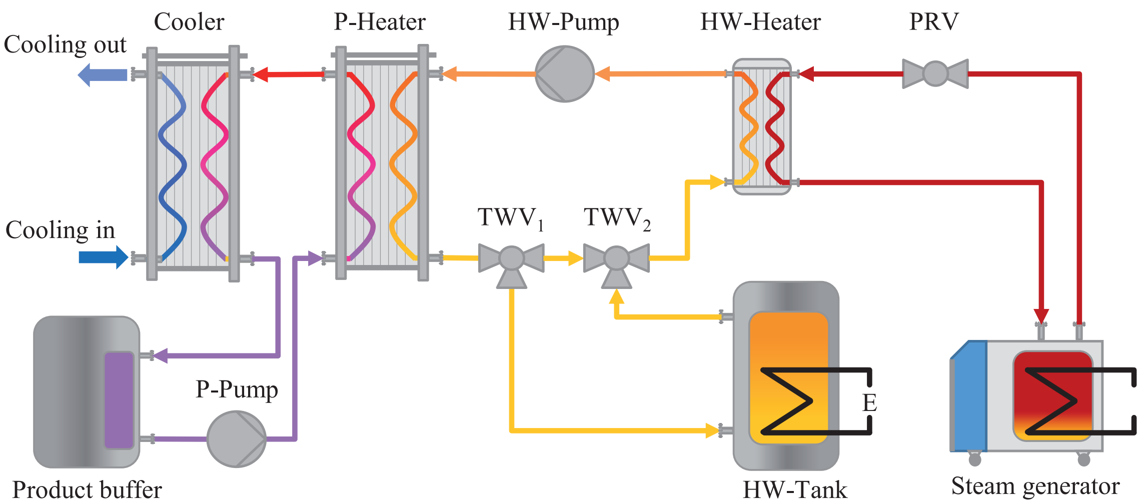

Figure 5. Schematic arrangement of the hydraulic instruments and devices for heat supply and transfer for the H²S prototype testing facility.

ER heat flows are calculated by temperature differences, flow rates and specific heat capacity. Property data are supplied online by the coupled simulation.

SIMULATION AND HIL METHOD FOR PROCESS INTEGRATION

In order to prove the functionality of the H²S concept under realistic circumstances prior to an installation in the process field, the H²S set-up has been integrated in validated MATLAB simulations for the pasteurization process as well as LTH sources such as CHP, HPs and electric boilers (Figure 6 and Figure 8). The MATLAB Simulink simulation software is used to build the testing environment that virtually supplies critical process conditions through the HW-Tank system. By this means it is possible to evaluate any conceivable integration concept and to prove the set-up during dynamic changes as well as in extreme situations. For its implementation, the exchange of process values is required in real-time. Data is sent from the simulation to the hardware and vice versa. The feedback of a so called hardware in the loop system can be realized by OPC (W. Chaaban et. al 2011). The installed PLC as well as Simulink support OPC. It is a standardized software interface for manufacturer-independent communication between different users, but still has four different specifications. For the connection to the Simulink OPC-toolbox the real-time compatible Data Access (DA) standard is used. Central actors of the OPC communication are the server and the clients. In this context the PLC acts as an OPC DA server, which provides any PLC values. Simulink acts as an OPC DA Client, which is able to read or write PLC values provided by the OPC Server. The Simulink OPC Toolbox offers a real-time block and prefabricated Writing and Reading blocks. In the context of networked H²S and the DR control system (Figure 3) the user-independent OPC is very well suited.

TEST SCENARIOS

Two test scenarios are defined to show the potential integration possibilities, HW-integration and DR management. As a result the influence of changing boundary conditions ($T_{H,H,o}$ and $\dot{Q}_{S,plus}$) on the target product temperature ($T_{P,P,o}$) are evaluated. This includes the test of the control algorithm on its reliability on reaching $T_{P,P,o,set}$ and the mutual influence with the model based supply side. The first scenario "HP" focuses on the confirmation of HW-integration from a heat-pump. Where the DR management scenario points out the possibilities of shifting the final energy mix from a large share of natural gas from CHP to a higher part of electricity from electric steam generator (ESG) using inexpensive electricity load that is shed from the grid.

Heat Pump Scenario

Pasteurization plants are usually well designed to recover most of the heat. For reaching the final temperature external heat is added and needs to be cooled back before storing the cold product after the process. In the dairy industry, chilled water is usually supplied by ammonia chillers. The condensation heat of the machines produces high amounts of LTH at 30–45 °C, which is usually rejected by cooling towers. Heat pumps can shift up the rejected heat and transfer it to HW with a temperature level of 60–75 °C using an extra compression stage. The heat from the desuperheater and the condenser are combined to heat up a stratified tank (ST). In this way it is possible to close a loop between heat supply and cooling. This form of closed circuits design with heat pumps has already been investigated by Kapustenko et al. (2008) and Becker et al. (2011). The HP concept demonstrates the H2S reaction on changing hot water supply temperatures. The developed simulation model of the hardware-in-the-loop (HIL) system consists of a HP, ST and the preheating and cooling section from the pasteurization plant. Figure 6 shows the HIL testbed structure and the connections to the testing facility via the OPC connection.

The temperature of the LTH source fluctuates depending on the source load profile. In order to optimize the COP, the HP performs a fixed temperature lift of 30 K. The modeling of the heat pump follows the change of state in the cold vapor process and is calculated on the basis of Cube (1997). Especially in the food industry there are many batch processes. Due to this time gap between source and sink a ST is used to buffer and smooth peak loads. In the scenario a ST model, based on (Duffie and Beckman 2013), is applied. In this manner the HP charges the ST at layers of equal temperature to ensure that there is no destruction of the temperature levels. The HW-feed is discharged at the highest possible temperature to the H²S. By virtue of a falling source temperature (from 45 down to 30 °C) of the HP, the ST discharges and $T_{H,H,o}$ decreases in the same way. Against this background the H²S has to achieve the pasteurization temperature TP,P,o with decreasing HW supply temperature. The preheating and cooling PHE of the pasteurization process are modeled on the basis of Kessler (1996) and VDI (2013). Within the scope of HIL evaluation $T_{H,H,o,set}$, $T_{P,P,o,set}$ and $T_{P,P,i,set}$ as well as the corresponding mass flows are written in the PLC in real-time depending on the behavior of the ST, HP, and production conditions. At the same time the actual values like $T_{H,H,o}$ and $T_{P,P,o}$ are read in Simulink and used as input variables balancing the discharging of the ST and the preheating PHE.

Demand Response Management Scenario

This second scenario demonstrates how the H²S reacts to demand response strategies, like the increased consumption of steam. The motivation for the DR is the participation in the balancing energy market. A step function as shown in Figure 7 is used to simulate a request for DR.

The virtual supply system, modelled in MATLAB Simulink, consists of a gas engine CHP, a natural gas boiler (NGB) and an electric steam generator (ESG) as shown in Figure 8. In times of DR management, the ESG is started replacing partial or all of the steam from NGB. By switching to ESG the share of electricity in the final energy mix is actively increased. The CHP supplies the HW for the LTH sinks, except when a surplus of steam is created. This happens when the ESG is switched on. The extra steam can be seen in Figure 7 as the difference between DR and HTH demand. In this scenario the company is commissioned for 5 MW and consumes 4.2 MWh for which they get paid.

The virtual demand profiles of LTH, HTH and DR interact with the prototype and the control of the Simulink model. Supply and demand data are constantly exchanged with the PLC. The changing heat supply of the H²S is fed back to the demand profiles, which affect the operation of the test set-up. In this simulation further virtual H²S systems are added. They follow the same logic like the hardware. Their change in ER interacts with the prototype's value to calculate ER_{total}.

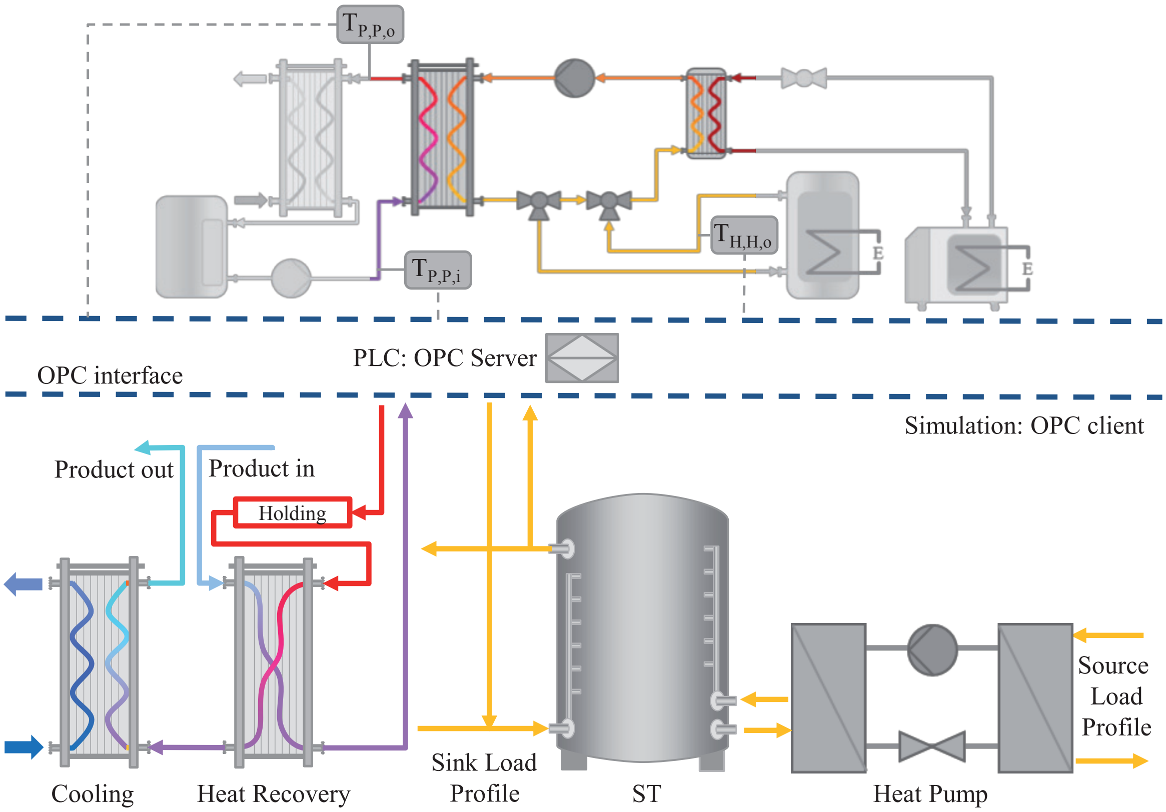

Figure 6. HIL-Integration of H^2S-System with a fluctuating heat source from HP and ST. (Below: model ambiance, top: H^2S-hardware, interconnected by OPC-Interface.)

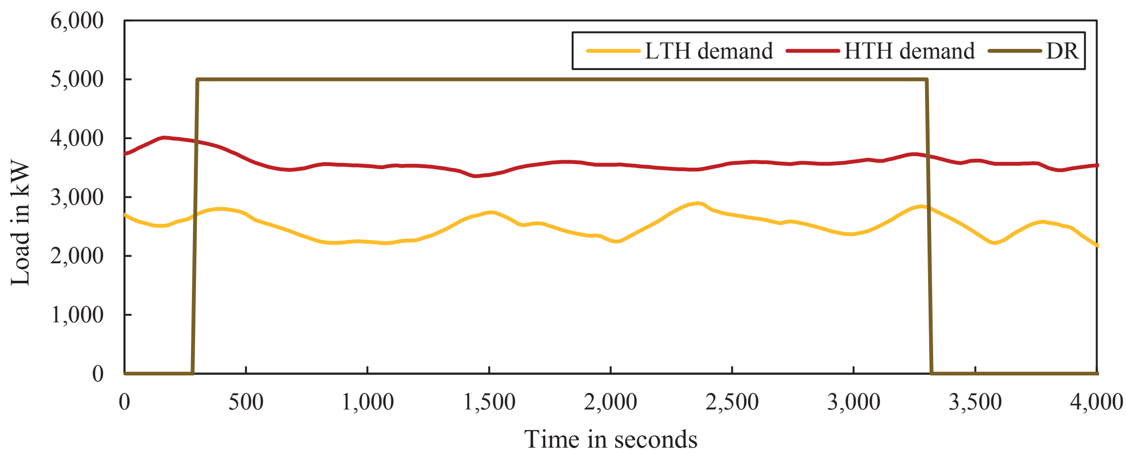

Figure 7. Thermal loads and demand response peak.

Results and Discussion

The aim of the experiments, in combination with numerical models, was to demonstrate the functionality and flexibility (for e.g. managing DR, LTH integration) of the H^2S system while meeting the requirements of the pasteurization process. The set temperature for the heater is 73 °C in both scenarios. An upper and a lower tolerance limit are defined and compared with the target temperature for the control's accuracy. For the lower limit, 72 °C is chosen as the minimum temperature for a pasteurization. For the upper limit, 74 °C is selected above which fouling and protein denaturation can cause quality degradation.

SCENARIO HEAT PUMP

For the present scenario, surplus HW potentials are available over the entire simulation time. Therefore the algorithm for the external ER is always calculated to 100 % (Equation 2). The continuous drop in source temperature leads to the presence of a temperature stratification in the ST. Because the hot water is discharged from the uppermost layer, always the highest

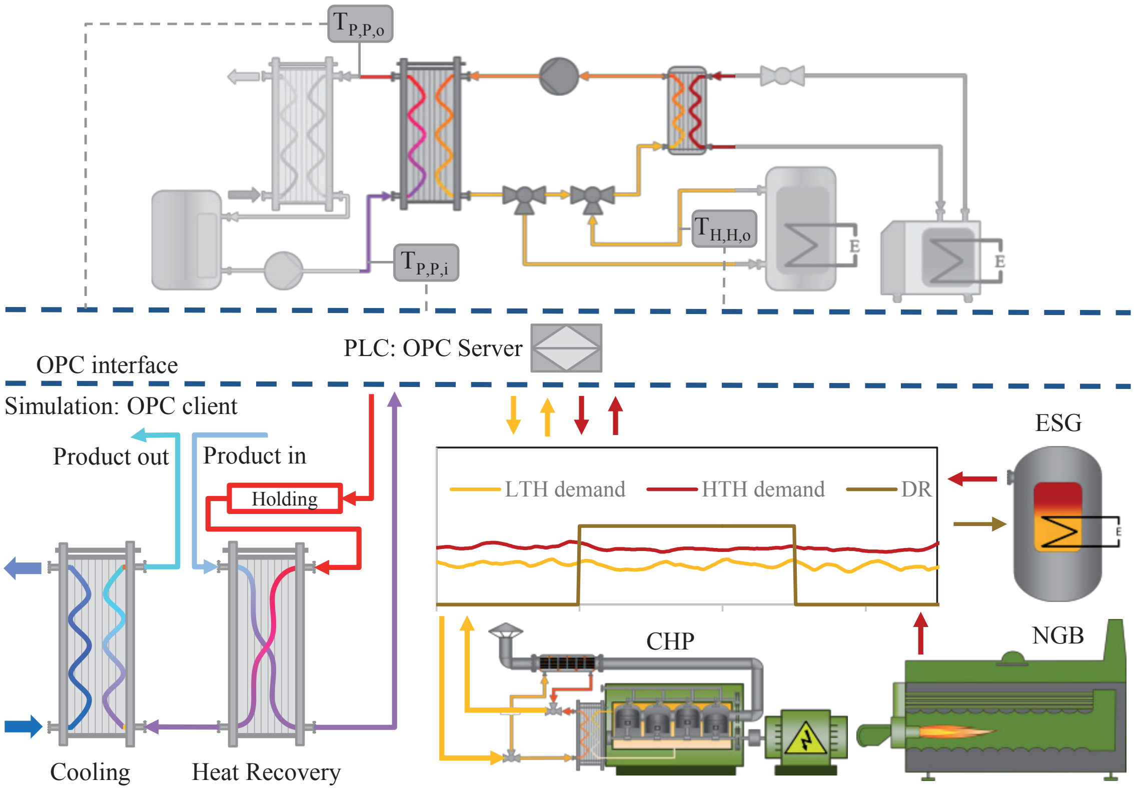

Figure 8. HIL-Integration of H²S-System with Demand Response Management and CHP for LTH supply.

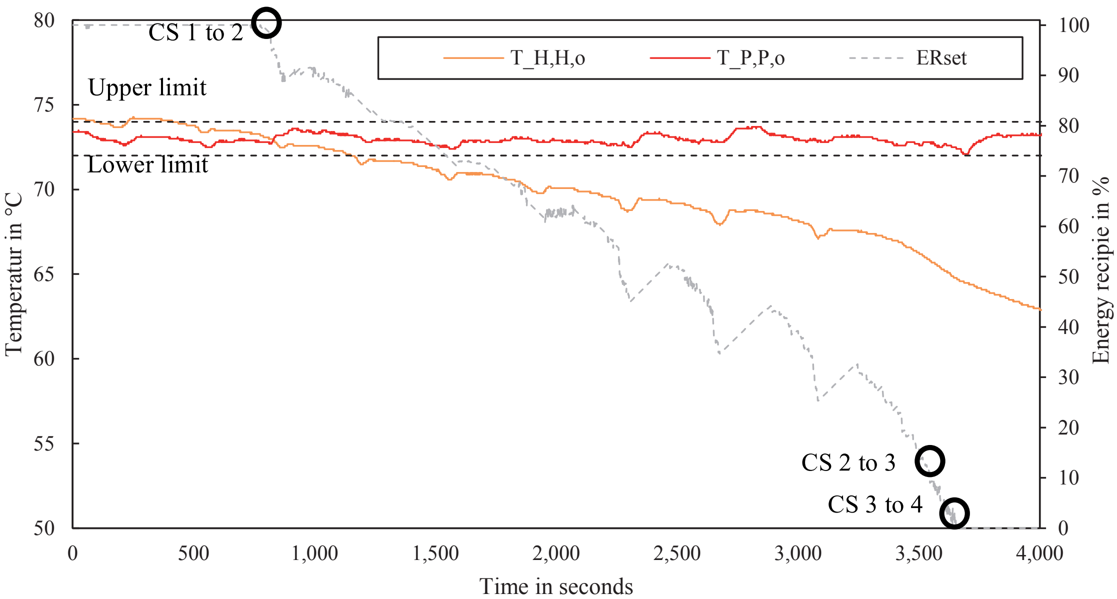

Figure 9. Impact of descending LTH temperature on the H²S and the pasteurization target temperature.

HW temperature is utilized. This supply temperature which decreases similar to the LTH drop is defined as the boiler set temperature for simulating the HW flow temperature $T_{H,H,o}$ and written in the PLC via OPC. The influence of this temperature drop on the energy recipe and the development of the pasteurization target temperature $T_{P,P,o}$ is shown in Figure 9.

$T_{H,H,o}$ drops from 74.8 °C to 62.8 °C before the TWV closes. When the target temperature cannot be achieved by the present hot water temperature, the H²S switches from CS 1 to CS 2 (ER = 99 %), in which steam duty is needed. From this point in time (800 s), the ER_{in} dominates the ER_{ex}. As $T_{H,H,o}$ continues to drop, less HW can be integrated. Hence the H²S control switches to CS 3 (ER = 10 %) and later to CS 4 (ER = 0 %). As a result the system is only supplied by steam.

The lowest value of 72.1 °C occurs at 3,700 s when switching to CS 4 and the highest value of 73.7 °C at 2,800 s, due to the fluctuations of $T_{H,H,o}$ in CS 2. The variation of the HW flow temperature, caused by the inertia and the control of the HW generation system, leads to logic changes in the ER_{in}. The control response of the system, even with fluctuating hot water potential and temperature, met in every case the requirements of the dairy industry. The product temperature is successfully kept between the lower limit of 72.0 °C and the upper limit of 74.0 °C. The average temperature is 73.0 °C ± 0.1 K with a mean absolute deviation of 0.2 K. Furthermore, Figure 9 shows that even with HW at 69 °C, 50 % of LTH can be integrated. Figure 10 shows a quantitative example for a process heat demand of 1 GWh per year. The higher the ratio of hot water integration, the lower is the final energy demand due to higher effectiveness of the heat pump. Where a maximum energy saving of 78 % is possible.

SCENARIO DEMAND RESPONSE STRATEGIES

The DR peak (see Figure 7) at 300 s causes the start of the ESG producing 5 MW of steam ($\dot{Q}_{S,ESG}$) influencing the ER_{ex} as shown in Figure 11. In the beginning of the scenario the CHP provides hot water for LTH sinks and the HTH sinks are provided with steam from the NGB. As soon as the heat output from the ESG reaches the HTH demand at 430 s a surplus of steam is created ($\dot{Q}_{S,plus}$). By this time, no more steam is produced by the NGB. The LTH sinks are assumed to be hybrid systems consuming the extra steam of approximately 1.5 MW. The switch to steam consumption is regulated by the ER_{ex} with an average value of 45 % during the peak.

In Figure 12 the trend of the target temperature is plotted together with the measured ER and the ER_{set}, following the ER_{ex}. The ER_{total} is the mean value of all H^2S representing the influence of the prototype on the whole DR system. To follow the ER_{ex} the control variation changes from CS 1 to CS 2 at 430 s and back to CS 1 at 4,300 s.

The product temperature is successfully kept between the lower limit of 72.0 °C and the upper limit of 74.0 °C. The average temperature is 73.0 °C ± 0.1 K with a mean absolute deviation of 0.2 K. The highest value of 73.7 °C is caused by the transition CS 1 to 2 and the lowest of 72.3 °C by switching back to CS 1. Closing and opening the steam valves causes the critical values. Depending on the process and the frequency of control transitions a minimum set value of the PRV in CS 1 could be

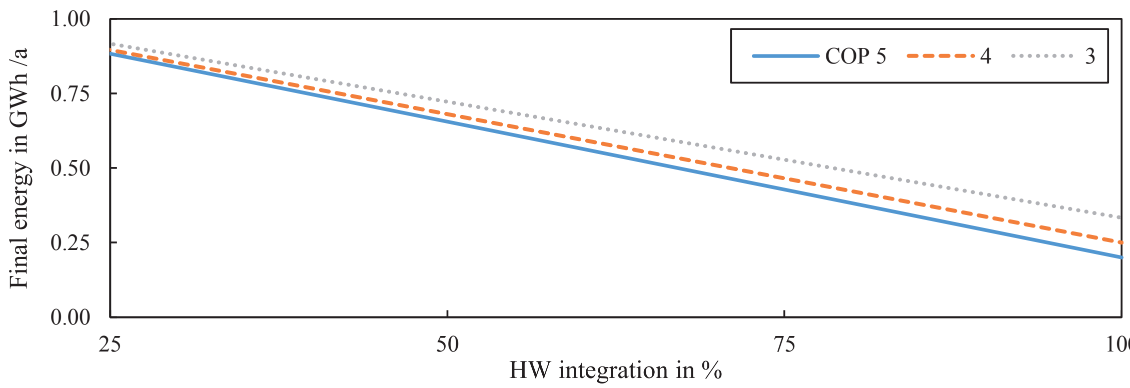

Figure 10. Relationship between ratio of water integration and final energy demand depending on the COP.

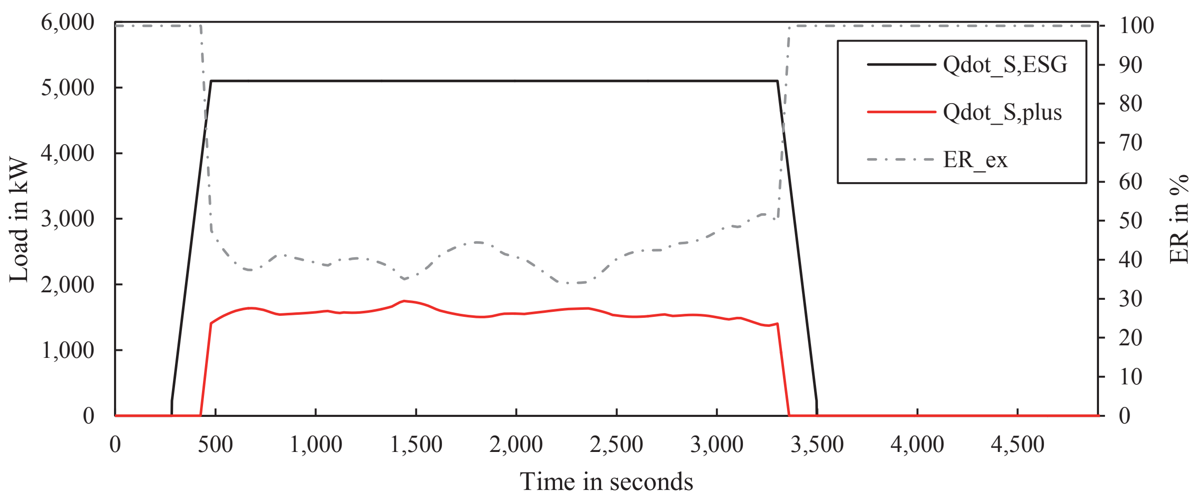

Figure 11. Generation of extra steam and the reaction on the supply strategy.

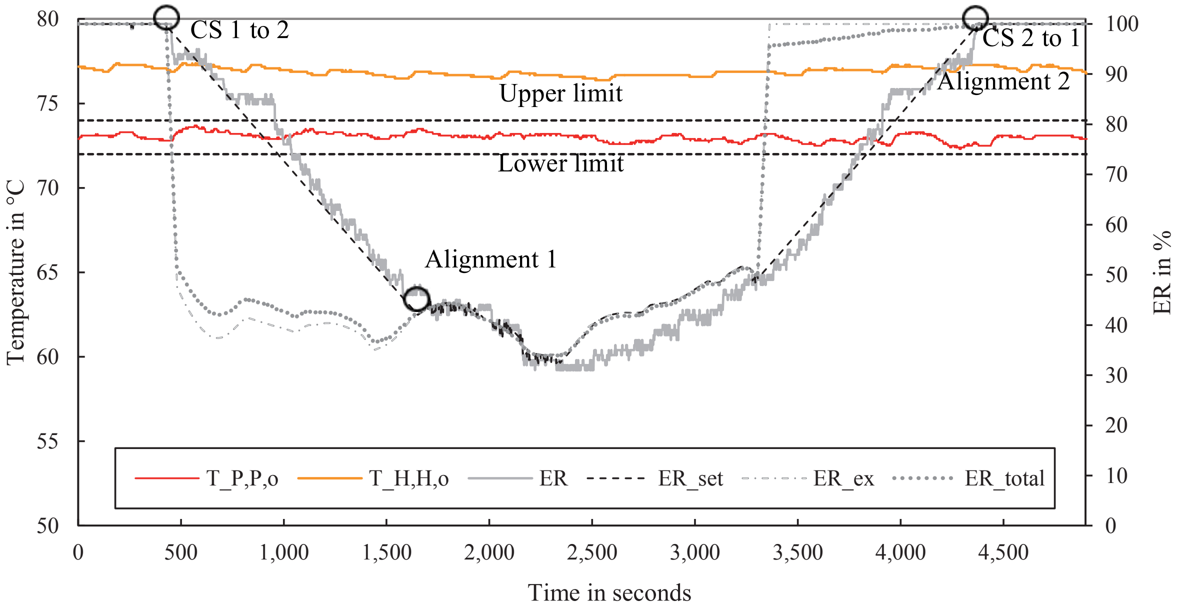

Figure 12. Reaction of the supply strategy of H^2S and development of the target temperature influenced by a surplus of steam.

necessary to avoid deviations. Besides these two changes in the control strategy most of the temperature fluctuation is related to the HW temperature profile ($T_{H,H,o}$).

In order to maintain the product's temperature no instant switch from 100 % HW to 40 % is possible. As mentioned before the pasteurization is a very sensitive process where reaching the target temperature has the highest priority. To met the product's quality the switch between hot water and steam has to be controlled. This is successfully achieved for all different ratios of HW and steam during this scenario. The implemented step function gradually aligned the ER_{set} to the ER_{ex}. The alignments take about 1,100 s (18.3 min) in this scenario. This result shows the limits to use a sensitive process like the pasteurization for demand response on the process. A system analysis of the total site is necessary for more detailed results on the dynamics of loads and sinks and the concept of multiple H^2S (Figure 3) for DR. The presented H^2S can be adapted to different process requirements by changing the speed of the step function. For less sensitive applications the changeover between the heat carriers is just a matter of the used valves and is typically carried out within a minute. Therefor further investigations need to be carried out on other LTH processes like the cleaning-in-place (CIP).

Due to the complexity of this topic the influence of the CHP was neglected in this scenario. The controlled reduction of the own electricity production is another option for DR. The combined DR with CHP and ESG gives a high potential for different strategies in this field. The interaction and the control of different supply systems for DR will be investigated and presented in future works. The focus of this paper is to demonstrate that the H^2S is a safe technology that opens a variety of new ways to manage the balance of supply and demand. It enables the direct utilization of surplus steam at the process and automatically uses efficient LTH when it is more reasonable. Other set-ups would require the installation of expensive steam accumulators or over dimensioned back-up heaters and storages for the hot water loop in order to deal with the extra steam. Because the redundancy is directly at the process and the H^2S control reacts to changes in the availability on the supply side, the sizing of storages and piping can be reduced to a minimum. This saves installation and maintenance costs and reduces transmission and transfer losses. A higher width of options and lower investment costs for the combination of efficient LTH technologies and the demand response with power-to-heat are the main benefits shown in this scenario. To quantify the financial potential of DR further calculations based on dynamic market data is necessary. Besides the economic gain for the consumer the energy efficiency on the regional level is increased by the use of renewable resources like wind and solar.

Conclusion

The Hybrid Heating System is designed for retrofitting heating systems for the implementation of low temperature heat and managing different heat supply systems. It increases the efficiency and flexibility on the thermal energy supply by integrating hot water from heat pumps, combined heat power and waste heat streams. The presented hardware configuration and the control algorithm are also suitable for the implementation of demand response strategies, switching from natural gas to increased electricity consumption.

A hardware-in-the-loop testbed environment based on OPC is successfully applied to evaluate the implementation prior to the real production field. The applied algorithm automatically sets the transitions between different control variations in order to integrate hot water and surplus steam, depending on their availability. In this context, the pasteurization temperature is met under dynamic changes and in extreme operating modes. The implementation of a heat pump, upgrading rejected heat, is evaluated in one scenario, showing that hot water can be utilized even when its temperature is below the product target temperature. By integrating hot water via the Hybrid Heating System, energy savings of up to 78 % can be realized. Another scenario shows that it supports the management of complex supply structures for heat generation, like it is necessary for demand response. The portions of steam and hot water used for covering the product's duty can be varied to match the current supply strategy.

The hardware-in-the-loop based evaluation demonstrates that low temperature heat technologies and heat supply management strategies can be applied by the Hybrid Heating System. This new system for the food and beverage industry guaranties full product safety and offers high benefits in energy efficiency.

References

B.KWK Bundesverband, 2011, Leitfaden zur Kostensenkung mit Kraft-Wärme-Kopplung in Molkereien, Bundesverband Kraft-Wäme-Kopplung e.V.

Becker, Helen; Maréchal, François; Vuillermoz, Aurélie, 2011, Heat pump integration in a cheese factory, in: Int. J. Thermo. Bd. 14. Nr. 2.

Broberg Viklund, Sarah, 2015, Energy efficiency through industrial excess heat recovery – policy impacts, in: Energy Efficiency. Bd. 8. Nr. 1, 19–35.

Cube, Hans L. v. (Hg.), 1997, Lehrbuch der Kältetechnik. 4., völlig überarb. Aufl. Heidelberg, C. F. Müller.

dena, 2011, Energy modernisation of industrial heating systems. Options for increasing efficiency and saving energy in large-scale combustion plants, Berlin.

Duffie, John A.; Beckman, William A., 2013, Solar engineering of thermal processes. 4. ed.,. Hoboken, NJ.

Johansson, Maria T.; Söderström, Mats, 2014, Electricity generation from low-temperature industrial excess heat – an opportunity for the steel industry. In: Energy Efficiency. Bd. 7. Nr. 2, 203–215.

Kapustenko, P.; Ulyev, L.; Boldyryev, S.; Garev, A., 2008, Integration of a heat pump into the heat supply system of a cheese production plant, in: Energy. Bd. 33. Nr. 6, 882–889.

Kessler, Heinz-Gerhard, 1996, Lebensmittel- und Bioverfahrenstechnik, Molkereitechnologie mit 109 Tabellen. 4. Aufl. München, Kessler.

Muster, Bettina; Ben Hassine, Ilyes; Helmke, Annabell; Heß, Stefan, 2015, Solar Process Heat for Production and Advanced Applications.

Philipp, Matthias; Schlosser, Florian, 2016, Forward-looking planning processes for more energy efficiency. Vorausschauende Planungsprozesse für mehr Energieeffizienz. This project (HA-Projekt-Nr.: 411/14-01) is funded in the framework of Hessen ModellProjekte, financed with funds of LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlich-ökonomischer Exzellenz, Förderlinie 3: KMU-Verbundvorhaben (State Offensive for the Development of Scientific and Economic Excellence).

Philipp, Matthias; Schumm, Gregor, 2014, Energy efficiency and emission reduction in the dairy industry through smart connections of heat flows. Energie- und Klimaeffizienz in der Milchindustrie durch intelligente Kopplung von Energieströmen. Gefördert durch: Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz; Bundesanstalt für Landwirtschaft und Ernährung; PT Innovationsförderung. Förderkennzeichen: 2817401911. Kassel.

Ramirez, C. A.; Patel, M.; Blok, K., 2006, From fluid milk to milk powder. Energy use and energy efficiency in the European dairy industry, in: Energy. Bd. 31. Nr. 12, 1984–2004.

Saravacos, George D.; Kostaropoulos, A. E., 2016, Handbook of food processing equipment, Second edition, Food engineering series, 1571-0297. Cham.

Schmitt, Bastian, 2014, Integration thermischer Solaranlagen zur Bereitstellung von Prozesswärme in Industriebetrieben. Schriftenreihe der Reiner Lemoine-Stiftung. Aachen.

Schumm, Gregor; Schlosser, Florian, 2016, CHP-friendly hot water supply concepts in the dairy industry. Klimafreundliche Lebensmittel durch KWK-gerechte Produktionsprozesse. This project (HA-Projekt-Nr.: 415/14-05) is funded in the framework of Hessen ModellProjekte, financed with funds of LOEWE – Landes-Offensive zur Entwicklung Wissenschaftlich.

Schumm, Gregor; Philipp, Matthias; Hesselbach, Jens, 2015, German utility model: Hybrid-Erhitzer – HE. 20 2015 001 143.

Silva, Filipa V.; Gibbs, P. A., 2009, Principles of Thermal Processing: Pasteurization, in: Simpson, Ricardo (Hg.): Engineering aspects of thermal food processing, contemporary food engineering, Boca Raton, 13–48.

Simpson, Ricardo (Hg.), 2009, Engineering aspects of thermal food processing, Contemporary food engineering. Boca Raton.

Sun, Da-Wen, 2012, Thermal food processing, New technologies and quality issues, 2nd ed, Contemporary food engineering, Boca Raton, FL.

VDI e.V., 2013, VDI-Wärmeatlas, 11., bearb. und erw. Aufl. VDI-Buch, Berlin.

W. Chaaban, M. Schwarz, B. Batchuluun, H. Sheng, J. Börcsök (Hg.), 2011, A HiL Test Bench for Verification and Validation Purposes of Model-Based Developed Applications Using Simulink® and OPC DA Technology.

Waheed, M. A.; Jekayinfa, S. O.; Ojediran, J. O.; Imeokparia, O. E., 2008, Energetic analysis of fruit juice processing operations in Nigeria, in: Energy. Bd. 33. Nr. 1, 35–45.d.