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Transition of Steam Utility Systems to Solid Biomass-Fuelled Boilers and Biomethane-Fuelled Fuel Cells in the Wet Pet Food Processing Industry

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This study highlights the CO_{2e} - emission reduction potentials and related economic consequences for changing the steam generation from fossil to renewable. Two different utility concepts are developed, including a steam accumulator for load management. The first concept integrates a solid biomass-fuelled boiler into an existing utility system with a natural gas boiler. The second concept uses a biomethane-fuelled fuel cell for the base load and a natural gas boiler as a backup boiler. A detailed process analysis and dimensioning of the technology and the accumulator is the basis for a dynamic simulation. In the simulation the steam accumulator volume is varied. In addition, the electricity usage of the fuel cell is optimized in terms of costs or emissions. The comprehensive simulation study is done for a pet food processing company having an average steam demand of 18,000 MWh at around 9 bar and 3 t/h. The results show that the CO_{2e} - emissions can be reduced up to 42 % by the transition to a solid biomass-fuelled boiler system and up to 27 % using a biomethane fuelled solid oxide fuel cell. This leads to an increase of the operating costs. The comparison of the reduction to the total costs resulted in 0.05 – 0.11 €/kg CO_{2e} - reduction per year for the biomass fuelled system and for the fuel cell in 0.69 – 1.14 €/kg CO_{2e} - reduction per year. To transfer these concepts to other cases, the scope of the study focused on covering a representative steam demand. The study shows that switching to renewable energy sources and implementing load management measures, emissions can be reduced at corresponding additional costs.

1. Introduction

As part of the global energy transition to limit climate change, the Paris Agreement envisages a reduction of greenhouse gas (GHG) emissions to 40 % by 2040, starting from the base year 1990 (European Commission, 2011). Process steam is widely used in the industry as the main supplier of thermal energy. It is currently still often generated by fossil-fired steam boilers for economic benefits. In 2016 around 21.4 % of Germany's total energy consumption is needed for process heat (BMWi, 2018). The share of renewable energies for process heating was only 5.2 % (BMWi, 2018). Energy efficiency and renewable energies are the two ways GHG emissions can be reduced. To reduce the energy demand, energy efficiency is particularly important in the low-temperature range regarding the use of heat recovery systems and efficient supply technologies (e.g. heat pumps, combined heat and power units (CHP)). The use of biogenic fuels, such as solid biomass, biogas and biomethane, offers great potential for reducing CO_2 equivalents emissions in the high-temperature heat supply by steam (Maaß et al., 2018). To limit the increase of the global temperature to 1.5 °C above pre-industrial level, the share of renewable energies in industrial utility systems must increase significantly (United Nations Framework Convention on Climate Change 2015). By 2050, the share of renewable energies in industry must rise to 63 % (IRENA and C2E2, 2015).
In the food processing industry, typical processes with a huge thermal energy demand are cleaning, drying, evaporation and distillation, blanching, pasteurization, sterilization, etc. (Rieberer et al., 2014). For providing the steam for these processes often natural gas boilers are implemented. The short reaction times of the

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boiler help to manage the fluctuating steam demand due to batch sterilisation processes. In many cases the sterilisation process is the main energy consumer of steam in a wet pet food processing company. A literature review and analysis of the sterilisation process revealed that the process has been optimized in terms of sterilization temperature, sterilization time, material properties, heating medium and heat transfer coefficient (Simpson et al., 2006). Furthermore, a detailed analysis of the starting temperature and heat recovery potential has been carried out (Peesel et al., 2016). Alternative technologies to produce process steam with renewable energies have already been studied individually. The integration of a steam accumulator for a solid biomass-fuelled CHP plant in industrial application improves the operation of the turbine as well as the share of supplied steam from biomass (Stark et al., 2018). The transition to renewable technologies, in combination with load management, has not been explored yet. The novelty of this study is the analysis of the CO_{2e} -emission reduction potentials and related economic consequences for changing the steam generation from fossil to renewable energy for a high volatile energy demand. Two different utility concepts are developed, including a steam accumulator for load management. The first concept integrates a solid biomass-fuelled boiler into an existing utility system with a natural gas boiler. The second concept uses a biomethane-fuelled fuel cell for the base load and a natural gas boiler as a backup boiler. A detailed process analysis and dimensioning of the technology and the accumulator is the basis for a dynamic simulation. In the simulation the steam accumulator volume is varied. In addition, the electricity usage of the fuel cell is optimized in terms of costs or emissions. The comprehensive simulation study is done for a pet food processing company having an average steam demand of 18,000 MWh at around 9 bar and 3 t/h. Considering changing prices and emissions of the local energy system is a novel approach for a dynamic cost and emission analysis for a volatile steam demand.

2. Description of technologies

This section briefly describes the technical functionality of the solid biomass - fuelled boiler, biomethane - fuelled fuel cell and a steam accumulator. Peculiarities for the integration into a steam system with fluctuating steam demand are explained and the models for the simulation study are described.

2.1 Solid biomass-fuelled boiler

For providing steam by solid biomass, it is burned in a modern biomass boiler. The heat, generated in the combustion chamber, is transferred to water via a heat exchanger and evaporated accordingly. The amount of steam to be produced is regulated by the amount of fuel supplied. If the amount is reduced or increased, there is a delay in the supply of steam. Although a reduction in demand results in a lower fuel supply, the remaining fuel in the combustion chamber is still used. With an increase of the steam, more biomass is fed into the combustion chamber, which ignites with a delay due to the increased quantity (Zahoransky, 2013). With these plants a wide range of performance can be covered, whereby strict regulations exist in Germany and plants larger than 1,000 kW are subject to approval (Schabbach and Wesselak, 2012). This is justified by the emission of nitrogen oxides and ashes, among other things, whereby large plants must be equipped with special exhaust gas purification filters. The amount of occurring pollutants depends on the choice of biomass and the moisture content of the fuel (Kaltschmitt et al., 2016). Wood pellets or wood chips are often used. These are characterised by their good storage properties and their relatively high energy content (5.21 kWh/m³). Irrespective of the energy source, a continuously operated system requires both a corresponding storage area and a supply chain for the fuel. Due to the low energy content of the biomass fuels, a large amount of fuel is required, depending on the plant design. The fuel demand of the biomass boiler E_{BM} depends on the steam demand $E_{Steam,Demand}$ for the boiler and the part load efficiency η of the operating state of the boiler $P_{BM,partload}$.

$$E_{BM} = E_{Steam,Demand} \cdot \eta\left(\frac{P_{BM,partload}}{P_{BM,max}}\right) \tag{1}$$

For the dynamic simulation, the change rate between two operating stages is limited and the thermal inertia is considered.

2.2 Biomethane-fuelled fuel cell

The number of newly installed fuel cells has been rising steadily for several years. Although the number of fuel cells in use is still relatively low compared to conventional energy generators, the constant research and development of the cells, for example in the automotive industry, contributes to the constant growth. Since the use of fuel cells does not lead to combustion or gasification, the emissions are reduced to a minimum. In addition, fuel cells are usually operated as a combined heat and power plant (Zahoransky, 2013). They provide both waste heat and electricity. The disadvantages are the very high investment costs and the short service life (Niakolas et al.,2016). Depending on the electrolyte used, five different fuel cell types can be distinguished: Alkaline Fuel Cell (AFC), Polymer Electrolyte Fuel Cell (PEFC/PEFMFC), Phosphoric Acic Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MFC) and Solid Oxide Fuel Cell (SOFC). The electrolyte has an influence on the operating temperatures, efficiencies and the costs of the fuel cell. For example, the operating temperature of a PEMFC is approx. 65-85 °C, while an SOFC fuel cell is operated at approx. 700-1000 °C. The operating temperature of the MCFC is approx. 600-700 °C. Accordingly, only the MCFC and SOFC are suitable for the steam supply. In this analysis a SOFC is used. It has good prerequisites for steam production due to its high temperatures and efficiencies. The amount of heat generated depends on the area of use and density of the cell, which varies depending on the operating point of the cell. Simplified, this represents the so-called heat-to-power ratio (HTPR), which describes the ratio of the electrical energy produced to the thermal energy (Liso et al., 2011). In the SOFC in particular, biomethane/ - gas is usable. Biomethane/ -gas contains small amounts of hydrogen, hydrogen sulphide and other trace gases. These pollutants contained in the gas can damage both the components of the fuel cell and normal engines and turbines. Therefore, it is necessary to treat the gas beforehand. For high-temperature fuel cells, the removal of the sulphur compounds is sufficient. Typical processes for desulphurisation include fermenters, bioscrubbers and activated carbon filters. In addition to desulphurisation and processing, it is necessary for most fuel cell types to reform the gas before use. This means that the methane is converted into hydrogen. For a SOFC, this process is not necessary because the reforming can take place within the cell. The fuel demand of the fuel cell E_{FC} depends on the steam demand $E_{Steam,Demand}$ for fuel cell and the part load efficiency η of the operating state of the boiler $P_{FC,partload}$. The electricity provided by the fuel cell $P_{EL,FC}$ is defined by HTPR and the thermal power of the fuel cell $P_{Steam,FC}$.

$$E_{FC} = E_{Steam,Demand} \cdot \eta(\frac{P_{FC,partload}}{P_{FC,max}}) \tag{2}$$

$$P_{EL,FC} = P_{Steam,FC} \cdot HTPR \tag{3}$$

The simulation model is based on energy monitoring data. In addition, the simulation scenarios are designed for a constant load and the system is not exposed to fluctuations and behavioural changes. The created fuel cell model is limited to the output data of a fuel cell, which are defined and influenced by the heat-to-power ratio, the electrical and thermal efficiency as well as the reaction, heat and start up times.

2.3 Steam accumulator

It is fundamental to consider the implementation of a steam accumulator for solid biomass-fuelled boilers and biomethane - fuelled fuel cell due to the difference between the steam demand of the process and the steam supply. When the production is higher than the demand, the steam accumulator is charged, increasing the pressure inside while at the same time part of the steam condenses. When the steam accumulator is discharged due to a deficit of steam production, the pressure inside decreases and part of the water evaporates. So, the pressure level of the steam accumulator defines the load-level of the storage. To estimate the behaviour of the steam accumulator, the equilibrium model of Stevanovic et al. (2015) is chosen (Eq.4). Even, the more complex but detailed non equilibrium model is available, Biglia et al. (2017) proposed the utilization of the equilibrium model. Depending on the mass and energy balance of the steam accumulator, the pressure change can be calculated. The equilibrium model calculates pressure p inside of the vessel with a constant Volume V. The mass balance $\dot{m}_{nB} = \dot{m}_{n,in} - \dot{m}_{n,out}$ and the energy balance $(\dot{m}h)_{nB} = (\dot{m}h)_{n,in} - (\dot{m}h)_{n,out}$ for liquid (1) and vapourous (2) considers the boundaries as evaporation enthalpy $r = h'' - h'$ is also considered to depicture the evaporation and condensation inside of the accumulator. With the specific volume the saturated liquid v' and vapourous v'' state, the total mass M is calculated.

$$\frac{dp}{dt} = \frac{(\dot{m}h)_{1B} + (\dot{m}h)_{2B} + \left(\frac{\frac{rV}{M}}{v'' - v'} - h\right)(\dot{m}_{1B} + \dot{m}_{1B})}{M\left(\frac{dh'}{dp} + \frac{\frac{V}{M} - v'}{v'' - v'}\frac{dr}{dp} - \frac{r}{v'' - v'}\frac{dv'}{dp} - r\frac{\frac{V}{M} - v'}{(v'' - v')^2}\frac{d(v'' - v')}{dp}\right) - V} \tag{4}$$

The steam accumulator is operated within a maximum pressure of 13 bar and a minimum pressure of 9 bar. A pressure difference of 4 bar is utilized. This pressure difference takes a significant influence on the storage capacity of the steam accumulator. During the simulation runs, different storage vessel volumes are considered.

3. Method

To quantify the CO_{2e} - emission reduction potentials and related economic consequences for changing the steam generation from fossil to renewable energy a dynamic simulation is developed. Two different utility concepts are developed, including a steam accumulator for load management. The first concept integrates a solid biomass -fuelled boiler into an existing utility system with a natural gas boiler. The second concept uses a biomethane -fuelled fuel cell for the base load and a natural gas boiler as a backup boiler. A conventional system with to natural gas boilers is used as a reference case. Figure 1 gives an overview of the design of the steam utility systems in the dynamic simulation. For both concepts, biomass and fuel cell, the steam accumulator is charged if there is a surplus of produced steam by the boiler or fuel cell and the pressure in the storage is below 13 bar. It is discharged, if the produced steam of the biomass boiler or fuel is less than the demand and the pressure in the storage is higher than 9 bar. In case the produced steam by one technology and the steam accumulator is less than the demand, the natural gas fired backup boiler is used.

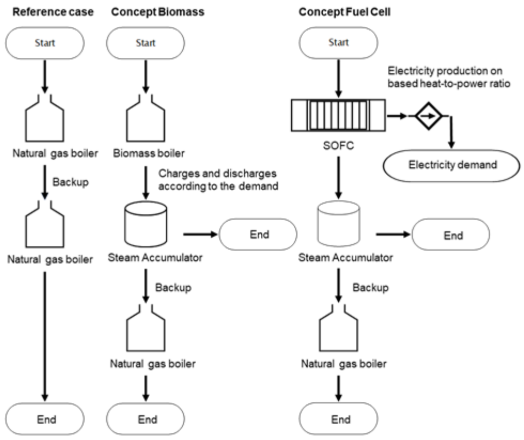

Figure 1: Overview of steam utility systems of the dynamic simulation

For the dynamic simulation Matlab/Simulink is used. Due to the strongly fluctuating demand profile of the considered application, the steam storage is considered in different sizes. The accumulator dimensioning is designed based on the average maximum overload and the maximum overload. These measures aim at offsetting all surplus and overload intervals by analysing all recorded intervals for one year. For the electricity provided by the fuel cell, both a cost-oriented and an emission-oriented variant are investigated. For this purpose the costs and emissions, of the generated electricity, are allocated via the “Finish Method”. These values are compared to the current market values. Depending on the orientation, the electricity produced is used for own needs or fed and sold into the grid. The corresponding electricity process results in accounting effects of the recorded CO_{2e} - emissions as well as economic effects for sales and purchases of electricity.
Investment costs are based on expert interviews, including all associated costs as well as set-up and commissioning cost. For the annual costs of the investment the straight-line depreciation for a period of 15 years for the boiler and 10 years for the fuel cell and the steam accumulator is applied. The annual costs for the biomass-fuelled boiler C_{BM} and the fuel cell $\mathrm{C}_{op,FC}$ are the sum of depreciation costs C_{depr}, the fuel costs for biomass p_{BM} and natural gas p_{NG}. The electricity generation costs $\mathrm{C}_{EL,FC}$ are added to the annual costs and the earnings from the usage of the generated electricity or selling $\mathrm{S}_{EL,FC}$ it to the grid are subtracted from the annual costs.

$$\mathrm{C}_{BM} = \mathrm{C}_{depr} + E_{Steam,BM} \cdot p_{BM} + E_{Steam,B} \cdot p_{NG} \tag{5}$$

$$\mathrm{C}_{op,FC} = \mathrm{C}_{depr} + E_{Steam,FC} \cdot p_{BM} + E_{Steam,B} \cdot p_{NG} + \mathrm{C}_{EL,FC} - \mathrm{S}_{EL,FC} \tag{6}$$

4. Use case Wet Pet Food

In the following, the process data of a wet pet food processing plant located in Spain is used to transfer the concepts. Approximately 27,440 t of steam and 7,800 MWh of electricity are required annually at this location. The steam is supplied at 9 bar and approximately 175 °C. The average steam demand is 3.1 t/h. However, the demand fluctuates between 1 t/h and 7 t/h. Higher peak demands up to 10 t/h occur rarely during the year. In the reference case, the steam is produced by two conventional natural gas boilers. One acts as the leading

boiler and the other one is a backup boiler. When the steam demand cannot be entirely satisfied by the leading boiler and its storage, the backup boiler supplies the rest. The steam produced is used for the retorts, the ovens, the fillers and the mixer heating, being the steam demand of the retorts the biggest of all by far. Table 1 summarises the investigated scenarios for the different steam accumulator volumes, the size of the new technologies and emission or cost optimal operation strategies. The concept of the fuel cell is examined with three different regulations regarding the electricity process. A biomethane - fuelled fuel cell is being investigated in a cost optimal (FC1) and emission optimal (FC2) manner. Furthermore, a fuel cell fuelled with natural gas is investigated cost optimal (FC3). For all three fuel cell scenarios, all eight variants are simulated. For the biomass – fuelled boiler only different accumulator and boiler sizes are analysed.
For the calculation of the operating costs the natural gas price varies between 0.027 €/kWh and 0.031 €/kWh. The biomass price is fixed to 0.028 €/kWh. For self-used electricity and sold electricity the Spanish stock market price of 2017 in each time step is considered. The emissions of natural gas are 241 g/kWh, of biomass 27 g/kWh and the emission for electricity are based on the grid electricity mix in each time step. This value varies between 90.13 g/kWh and 486.49 g/kWh.

Table 1: Examined biomass and fuel cell concept variants with variable dimensioning of power and accumulator size

Use Case	Steam Accumulator	Concept Biomass		Concept Fuel Cell	
		Biomass boiler	Natural Gas Boiler	Fuel Cell	Natural Gas Boilers
	in m³	in kW	in kW	in kW	in kW
Reference Case	-	-	2 x 5432	-	2 x 5432
V1	25	410	5432	410	5432
V2	50	820	5432	820	5432
V3	75	1230	5432	1230	5432
V4	100	1640	5432	1640	5432
V5	120	1950	5432	1950	5432
V6	130	2055	5432	2055	5432
V7	135	2055	5432	2060	5432
V8	215	2055	5432	2060	5432

5. Results

For dynamic simulations of one year, both the biomass and the fuel cell have an optimal set up in terms of steam accumulator size and technology size. For the biomass concept, variant 6 is the best option with total yearly costs of 1,505,058 € and 4,025,962 kg CO_{2e}. An expansion of the storage tank over 130 m³ is not resulting in significant changes in costs and emissions. The costs rise steadily up to variant 5 with an increase of approximately 5 %. All concepts exceed the operating costs of the reference case. Consequently, none of the renewable energy concepts can achieve cost savings. The biomass variants and the natural gas fuel cell have the lowest costs. These exceed the costs of the reference case for the largest configuration by 25 % (BM) and 26 % (FC3). The variants operated with biomethane (FC1-2) have significantly higher costs. In this case, the largest design results in a cost increase of approximately 330 % compared to the reference case. In terms of CO_{2e} - emissions savings, three of the four concepts reduce the emissions. However, the concept of the natural gas-powered fuel cell causes higher CO_{2e} - emissions due to the lower efficiency compared to the reference case and shows an increase of 30 % in the largest design variant. The concepts of biomass and FC2 show the greatest savings potential. In the largest design variant, the use of biomass can reduce emissions by approximately 42 %. The emission-controlled fuel cell operated with biomethane has a saving potential of approximately 22 %. The ratio of additional costs to emission savings is shown in
Figure 2. The costs are offset against the corresponding CO_{2e} - reduction in order to obtain the costs per kilogram of CO_{2e} saved.

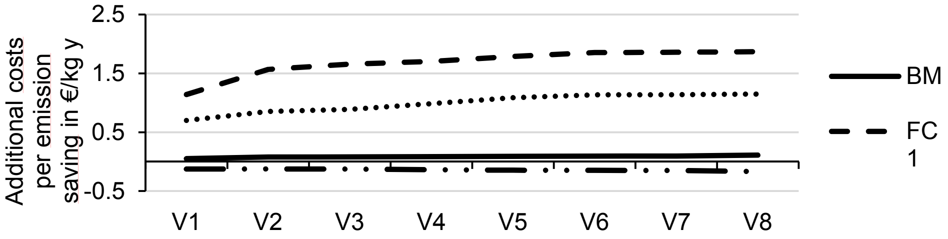

Figure 2 Costs for CO2e emissions savings per kg and year

For FC3, both costs and CO_{2e} - emissions increase. This option does not meet the objectives of the use case and is not analysed in further detail. The most economical savings are achieved with the biomass concept. The costs per saved kilogram of CO_{2e} per year are between 0.05 € and 0.1 €. The costs of FC1 are correspondingly 1.14 € to 1.88 € and those of FC2 0.69 € to 1.14 €. According to this, the use of a biomass boiler is the most efficient way of providing steam in terms of economic efficiency and CO_{2e} - emissions avoided. Variant FC2 is also the most economical and efficient variant considering all fuel cell concepts. It is more cost-intensive compared to the use of biomass.

6. Conclusions and outlook

The results show that the CO_{2e} - emissions can be reduced up to 42 % by the transition to a solid biomass-fuelled boiler system and up to 27 % using a biomethane fuelled solid oxide fuel cell. This leads to an increase of the operating costs. The corresponding analysis of the fuel cell shows an emission reduction of 35 % and an increase in total costs of 225 %. The comparison of the CO_{2e} - emission reductions to the total costs results in 0,05 - 0,11 €/kg CO_{2e} - reduction per year for the biomass fuelled system and for the fuel cell in 0,69 - 1,14 €/kg CO_{2e} - reduction per year. Subsequently, an analysis of the design dimensions is carried out. This shows that both technologies have different, optimal design parameters depending on the demand profile. The reductions in CO_{2e} - emissions decrease as a function of the increase in costs. For the biomass concept, the optimal demand coverage was 93 % and for the fuel cell 59 %. Since these values are strongly dependent on the demand profile, the optimum design size for each individual application must be determined. For the detailed evaluation and analysis of the transmission of renewable energies in accordance with load management to steam processes, it is necessary to investigate further technologies and technology combinations in subsequent steps. These could bring further advantages, especially regarding load management and grid stabilisation. Due to their inertia, the analysed technologies do not show any potential for grid stabilisation. Soon, concepts of the fuel cell will become more attractive. Due to the strong development and research in this area, significantly decreasing investment costs and increasing efficiencies are predicted until 2030.

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