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Decarbonizing Process Heat Supply in the Austrian Pharmaceutical Industry

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Abstract. In the pharmaceutical industry, energy efficiency has played a minor role compared to other energy-intensive industries. However, there is a growing recognition of the need to address environmental concerns. With ambitious climate targets and the increasing demand for significant reductions in CO2 emissions, the pharmaceutical industry is now embracing the opportunity to enhance its sustainability practices. Mainly fossil fuels are used to provide process steam at moderate temperature levels at about 160-180°C and to a lesser extent to provide hot water or for on-site power production in CHPs. In this paper, the main processes with demands for process heat, such as media supply, cleaning, or air conditioning, are presented and possibilities for increasing efficiency, for switching to alternative heat supply and for using alternative process technologies are evaluated with respect to economics, but also regarding hurdles for implementation such as requirements for revalidation of production processes and possible necessity of re-approval of products.

The present study highlights the potentials for decarbonization of the Austrian pharmaceutical industry using a generic but representative production site applying various measures that either reduce heating and cooling requirements or alter the temperature requirements for heat supply. It is shown that, at least for the example case, full decarbonization is technically feasibly without an increase in energy costs if efficiency measures are progressively used on demand level.

Keywords: Energy Efficiency, Heat Pumps, Decarbonization

1. Introduction

The driving motivation and background for conducting this study is the long-term reduction of greenhouse gas emissions in the pharmaceutical industry in the most economical way possible. Companies in the domestic pharmaceutical industry have ambitious targets and some companies want to be CO_2-neutral by 2025 considering scope 1 and 2 emissions. The manufacturing pharmaceutical sector in Austria is responsible for at least 1.5% (own calculation) of natural gas consumption in the domestic industry, with natural gas mainly used to provide process steam and heating. Typical energy supply systems in the production of pharmaceutical products are gas-fired steam boilers for the provision of process heat and chillers for the provision of the required cooling capacity for air conditioning and production. Steam from the boilers is used, among other things, in so-called black steam converters to generate pure steam, to heat water and alkalis in cleaning-in-place (CIP) systems, to generate water-for-injections (WFI) and pure steam, which in turn is used, for example, for room air conditioning, and in some cases for space heating. The energy input for CIP systems in dairy processes, for example, is about 9-26% of the energy consumption [1]. A similar order of magnitude can be expected in the pharmaceutical sector. The inlet temperature of the media (caustic solutions, acids, rinsing water) is rarely higher than 80°C, as this can jeopardize the stability of the media used [2]. For the U.S., the energy consumption of a drug manufacturing facility is distributed among space conditioning 65% (HVAC), lighting 10% and production 25% [3]. Several studies focused on the improvement of air exchange rates based on occupancy [4,5,6] and others highlighted heat recovery of exhaust air as promising measures to increase energy efficiency [5,7]. Hindiyeh et al. [8] focussed on eliminating non-added value steps in tablet production reducing greenhouse gas emissions by 73.2% for the respective process steps.

Even though the pharmaceutical industry yields large potentials for an increase in efficiency and for decarbonization, published work on these topics is sparse. Especially the use of heat pump technology to supply low temperature process heat has not been emphasised in literature, even though process temperature requirements are suitable for cost effective operation.

2. Methodology

In this paper, typical consumers of process heat in the pharmaceutical industry are presented and possible decarbonization alternatives are compared. These include measures to increase efficiency such as direct heat recovery, alternative heat supply such as heat pumps and electric boilers, but also technology changes that either enable a change in heat supply in the first place, or directly reduce the heat demand altogether. However, the identified measures need to be evaluated within the interconnected local energy system. Thus an MILP-based optimization model of the entire local energy system is used that allows to evaluate the benefits of the proposed measures from a system's point of view.

2.1. Reference Energy System

The reference energy system considered in this paper is a simplified system but contains the most energy intensive processes and the typical energy supply units of many pharmaceutical production sites. For energy supply there are natural gas fired steam boilers, natural gas fired hot water boilers and chillers to supply cooling for HVAC and production units. The main cooling and heating requirements stem from HVAC systems, CIP systems, WFI distillation systems and clean steam generators. HVAC systems often operate at fixed setpoints for temperature and humidity and a typical recirculation rate of 80%. Due to the high air exchange rates required, these systems are usually those with the largest heating and cooling requirements. Heat recovery is often not implemented. Humidification of air is performed using either clean steam or plant steam. CIP systems are usually connected to the plants steam distribution system and use steam to heat up media for a caustic rinse up to 70°C. In these systems, usually no heat recovery measures are implemented. WFI generation is performed in distillation systems using steam at around 7 bar and together with steam powered clean steam generators these units define the minimum steam pressure in the pharmaceutical steam distribution systems.

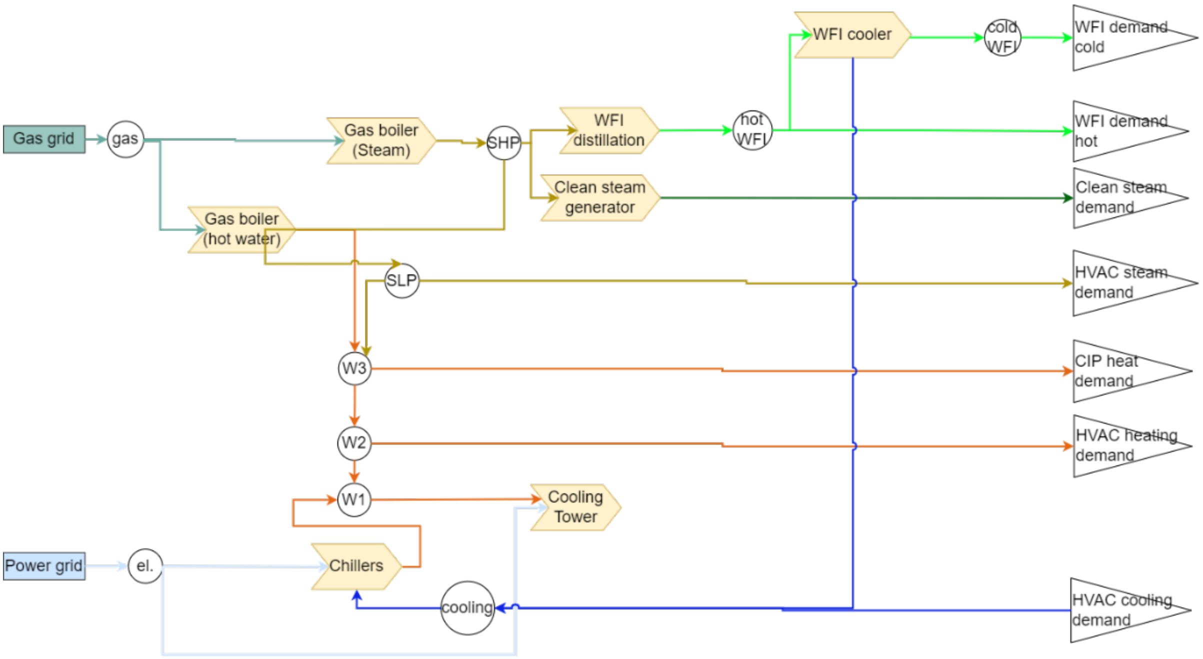

***Figure 1**: Simplified layout of the reference energy system.*

Figure 1 shows a simplified layout of the energy supply and demand system considered as a reference case. It needs to be stated, that in real systems additional heating requirements need to be considered for autoclaves and washing units and depending on the products, significant energy demands are to be considered for e.g., fermenting processes and dryers. In some cases, solvent recovery by means of distillation processes is performed requiring process heat at above 100°C. Wastewater treatment also often requires thermal inactivation.

2.2. Measures for Decarbonization

At the core of this paper are the different changes that could be applied to the refence system. On the supply side, the integration of heat pumps to supply process heat with different heat sources such as ambient air or excess heat from existing chillers are considered. Furthermore, electric boilers can be implemented as decarbonization measures for heat supply. Since heat pump efficiency strongly depends on the temperature lift, they need to overcome, additional heat distribution systems at moderate temperature levels are considered to increase exergy efficiency of the overall system. On the demand side, heat recovery in CIP systems is considered that directly reduce heating requirements for the caustic rinse, set points in the HVAC systems can be altered and heat recovery from the exhaust air and fresh air pretreatment can be introduced to increase energy efficiency. As an alternative to WFI production in distillation columns, membrane technology can be used to generate WFI with sufficient quality without the need for high pressure steam. To produce clean steam, electric clean steam generators can be used instead of steam powered ones. The extended energy system including all these options is shown in **Figure 2**.

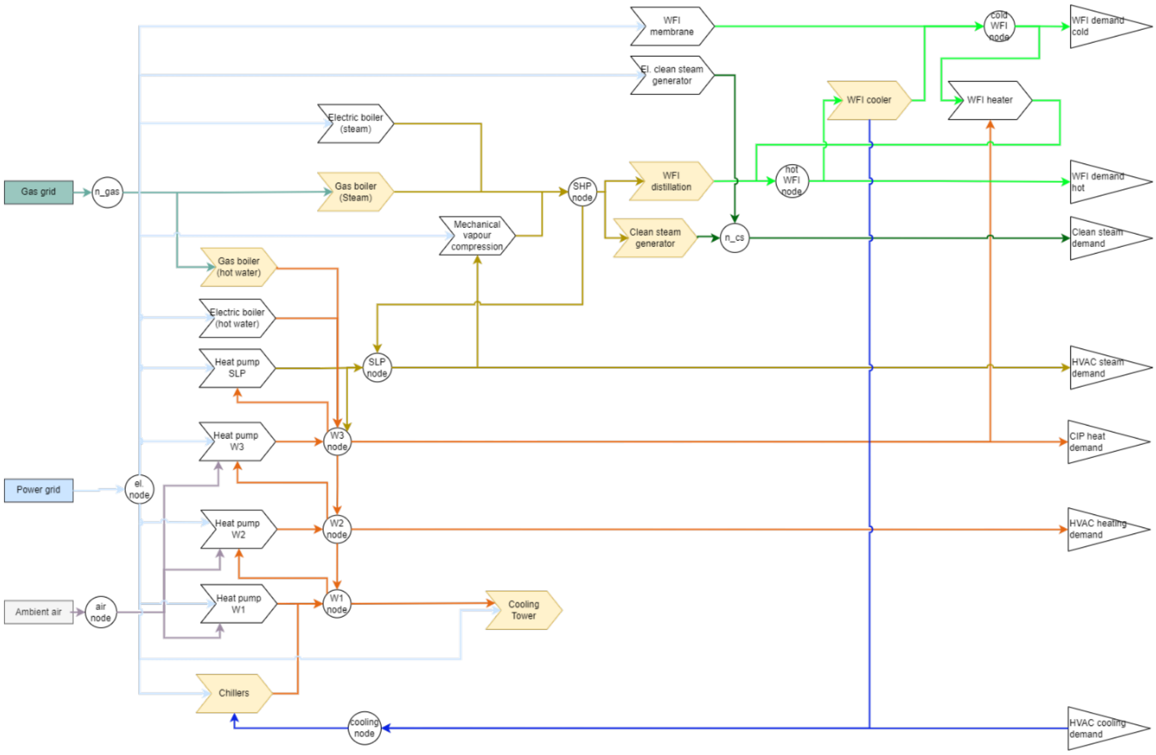

***Figure 2**: Simplified layout of the reference energy system (yellow units) and considered extensions.*

2.2.1. Difficulty levels for changes

In the pharmaceutical industry, process security and product quality are the most critical aspects when it comes to implementing energy efficiency and decarbonization measures. To address these considerations, all measures considered in this work are categorized in three levels reflecting potential impact on the production process. These levels are (1) the change does not affect any production parameters and are thus low risk measures, (2) process parameters are altered and thus production processes might require revalidation, which can cause significant efforts, and (3) chances that can be seen as very critical due to uncertain effects regarding quality such as adiabatic humidification in HVAC systems or due to regulative restrictions such as a change from distillation based WFI production to membrane based production. Especially membrane based WFI production is not allowed in certain international markets. **Table 1** summarises the proposed measures for decarbonization and their assigned classification.

***Table 1:** Assignment of considered decarbonization measures to difficulty levels of implementation.*

Description of decarbonization measure	Level 1	Level 2	Level 3
Changes in the energy supply system (new energy conversion units, new storage units, additional heat transfer systems)	X		
Heat recovery in CIP systems	X		
Heat recovery in HVAC units	X		
Fresh air pretreatment in HVAC units	X		
Altered set points in HVAC units		X	
WFI production using membrane technology			X
Adiabatic humidification in HVAC units			X

2.2.2. Heat recovery potentials in CIP systems

In CIP systems, the cleaning process usually involves a caustic rinse, which is followed by an acid rinse and then a final rinse is performed using WFI. Especially the caustic rinse is performed at elevated temperatures, usually at around 70°C. After each wash, the media are considered wastewater and are sent to a neutralization unit that ensures that the pH-value of the wastewater fulfills regulatory requirements. The return temperature of the caustic rinse after contact with the equipment requiring cleaning is reduced due to heat transfer to the equipment and due to heat losses in piping.

However, there is still significant potential to buffer the warm media from the caustic rinse to heat up new media for the next caustic rinse. To evaluate heat recovery potentials, a simple simulation model was set up (**Figure 3**) and different parameters such as media volume per rinse, temperature loss in the equipment, frequency of CIP runs and insulation for the buffer tank were examined. Results showed that considering moderate insulation of the buffer tank using rock wool and one to five CIP runs per day, around 30% of the heating demand for the caustic rinse can be covered (**Figure 4**).

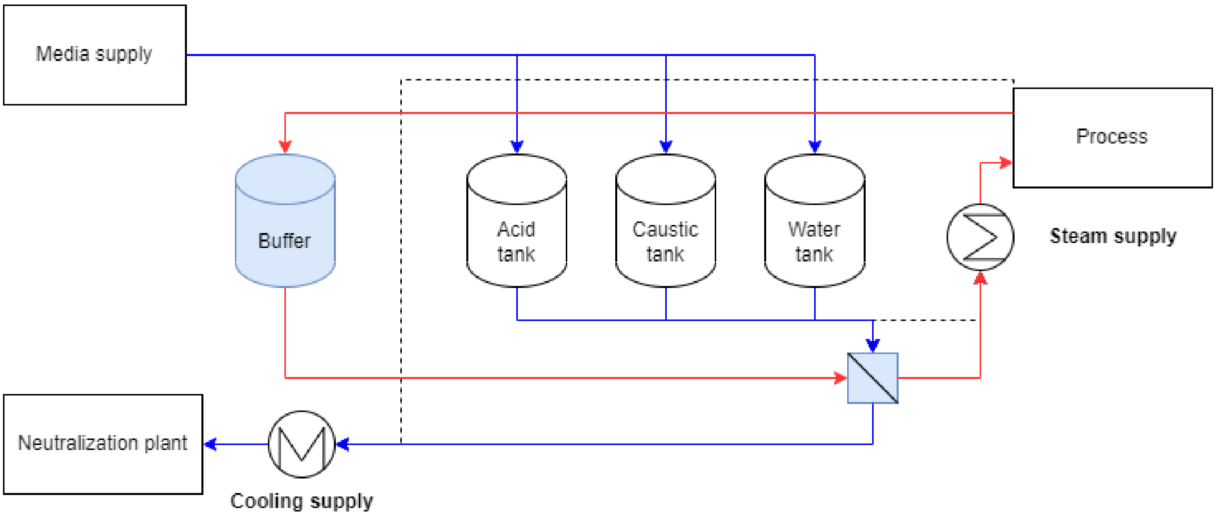

Figure 3: *Schematic of a CIP system including heat recovery system (highlighted in blue).*

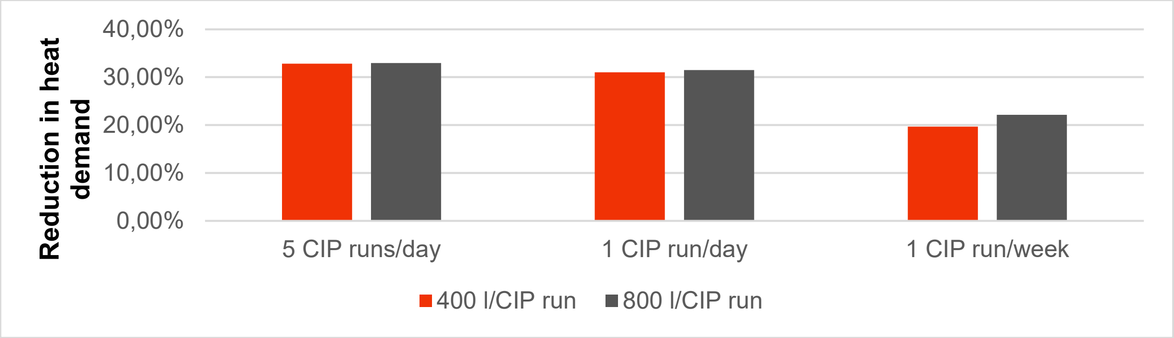

Figure 4: *Heat recovery potential in CIP systems with respect to media volume and frequency of CIP runs.*

2.2.3. HVAC systems

Efficiency measures for HVAC air handling systems were evaluated with a simplified model set up in Python. Since in these systems very large quantities of air are conditioned and usually 20% of the recirculated air is fresh air, most of heat losses and gains stem directly from ambient air conditions. For simplicity reasons, gains and losses due to conduction through the building walls or due to room occupation were neglected.

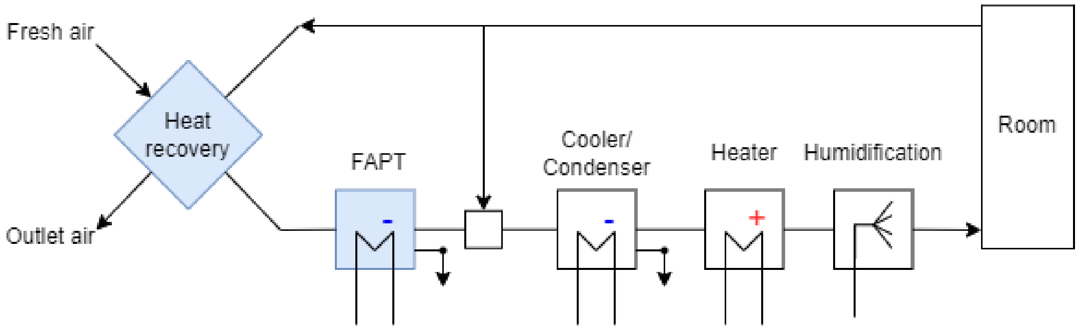

***Figure 5**: Basic HVAC system including efficiency measures (highlighted).*

For the refence case a system with a total air flow of 1m^3/s was considered with a fixed setpoint for temperature of 22.3°C and 53% relative humidity. The recirculation rate was set to 80% meaning that 20% of the total volume flow is fresh ambient air. For ambient air conditions, weather data from Vienna, Austria for 2021 were considered. In the reference system, the total air flow after mixing of recirculation air and fresh air is conditioned through a cooling and condensing section, a heating section, and a steam humidification section. The overall schematic of this HVAC system is shown in **Figure 5**.

For this work, three modifications to the system were evaluated. An additional fresh air pretreatment section (FAPT) was considered as an efficiency measure that is used for dehumidification of the fresh air. Also, a heat exchanger to recover heat from the exhaust was considered with an efficiency of 60%. This efficiency Φ is defined through

(1)

$$\Phi = \frac{T_{in} - T_{amb}}{T_{out} - T_{amb}}$$

where the subscripts in and out represent the inlet and outlet air and T_{amb} is the ambient air temperate. Furthermore, the fixed setpoint was extended to a setpoint range with 19-24°C for temperate and 40-60% relative humidity.

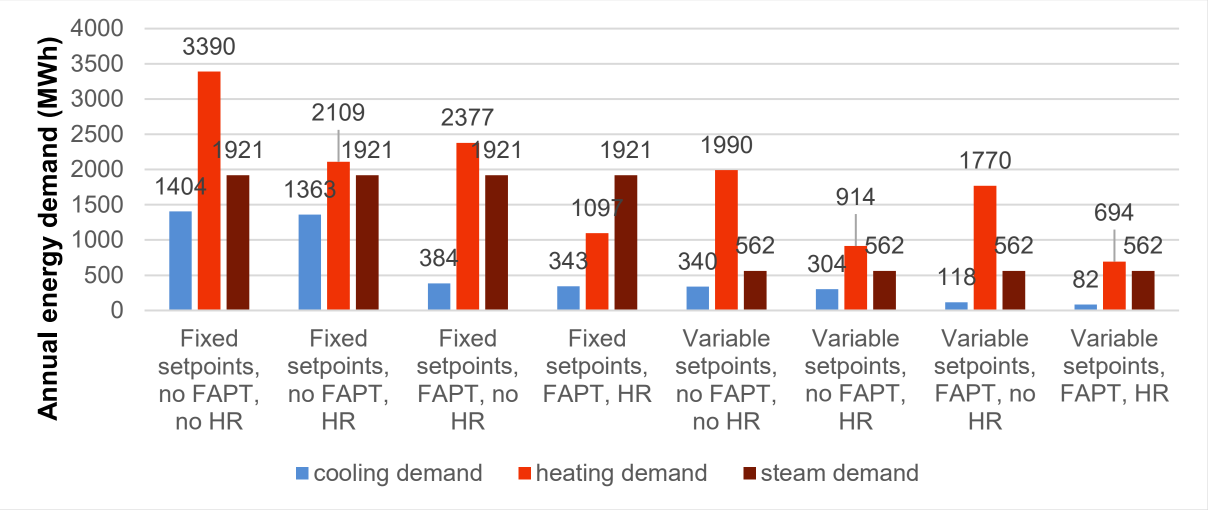

***Figure 6:** Heating, cooling, and steam demand for a reference HVAC unit with different measures for improvement of energy efficiency.*

The results presented in **Figure 6** show a significant potential for a reduction in heating requirements of around 38% due to the implementation of a heat exchanger for heat recovery, whereas a drastic reduction in cooling requirements of around 73% can be obtained using a FAPT unit due to the reduced air volumes that need to be cooled for dehumidification. In addition, allowing for a broader range of temperatures and relative humidity most significantly reduces steam consumption for humidification by 71% and cooling requirements for dehumidification by 77%. If all measures are fully exploited, cooling demands can be reduced by 94%, heating demands by 80% and steam demand by 71%. It needs to be emphasised that these results do not consider thermal losses or gains through the building envelop or the extra heat and moisture contribution from room occupancy or from processing equipment.

3. Results

To evaluate the proposed decarbonization measures in the context of the local energy system, seven scenarios were defined that employ the different decarbonization measures starting with the reference case described in Section 2.1. For each of the following scenarios additional decarbonization measures were added according to **Table 2** and the extended energy system described in Section 2.2. In Scenario 7, the system is based on the decarbonization measures allowed in Scenario 1 but full decarbonization is enforced.

Table 2: *Scenario description and related difficulty level for implementation of decarbonization measures.*

Scenario	Description	Level
0	Reference case	-
1	Heat pumps allowed	1
2	New distribution system at 90°C	1
3	Heat recovery in CIP systems, FAPT and HR for HVAC, electric clean steam generators	1
4	Set point ranges for HVAC	2
5	Membrane technology for WFI, adiabatic humidification for HVAC	3
6	Enforced full decarbonization	3
7	Scenario 1 with enforced full decarbonization	1

3.1. Model parameters

For the optimization model temporal profiles for 12 selected representative days were considered for ambient air conditions and heating and cooling demands. The reference case has a total heating requirement of 10 GWh per year which stems from the individual processes listed in the following:

- CIP: 10% / 1 GWh (fluctuating demand on weekdays between 5 and 18 o’clock),
- Clean steam: 15% / 1.5 GWh (fluctuating demand between 5 and 18 o’clock),
- WFI production using distillation: 20% / 2 GWh (fluctuating demand between 5 and 18 o’clock),
- HVAC – heating and steam: 55% / 5.5 GWh.

The requirements for HVAC derived using the reference model were scaled up.

Several heat distribution systems are considered in the system that can be used to supply process heating and cooling, depending on the scenario:

- High pressure steam (SHP): 180/125°C,
- Low pressure steam (SLP): 150/115°C,
- Hot water 3 (W3): 90/80°C,
- Hot water 2 (W2): 65/55°C,
- Hot water 1 (W1): 30/25°C,
- Cooling water: 6/12°C.

The investment costs is 200 €/kW for electric steam boilers, 150 €/kW for electric hot water boilers, 400 €/kW for hot water heat pumps and 600 €/kW for both the SLP heat pump and the mechanical vapour compression system. The annualization period considered in this study is 10 years. Natural gas costs are 40 €/MWh and electricity costs 100 €/MWh. The split between hot and cold WFI demand is 80/20 at WFI temperatures of 80°C and 20°C respectively. It is assumed that the steam distribution system has a storage capacity of 10 MWh. Heat pumps are assumed to have a second law efficiency of 50% and WFI generation using distillation is assumed to have an efficiency of 80% with respect to steam consumption. Membrane based WFI generation consumes 6.75 kWh/m³ WFI according to [9].

3.2. Scenario analysis

The capacities selected within the cost-optimized solutions for new energy supply units are shown in **Figure 7**. The total new capacities depend on the decarbonization measures allowed but merely exceed 0.75 MW in total additional capacity in scenarios 1-5. Enforcing full decarbonization requires 1 MW additional capacity for Scenario 6 and even 3.7 MW for Scenario 7.

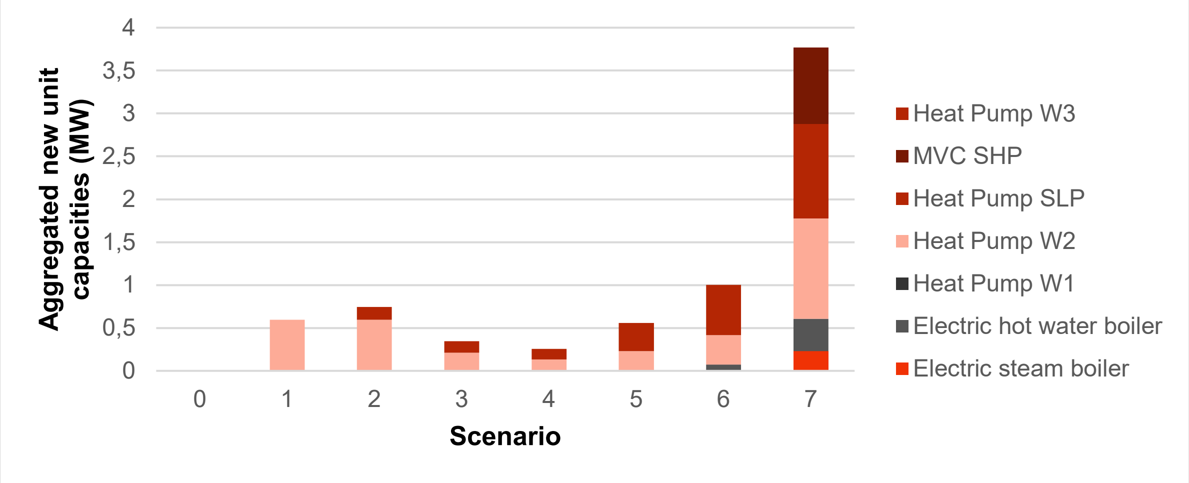

Figure 7: *Aggregated new unit capacities for all considered decarbonization scenarios.*

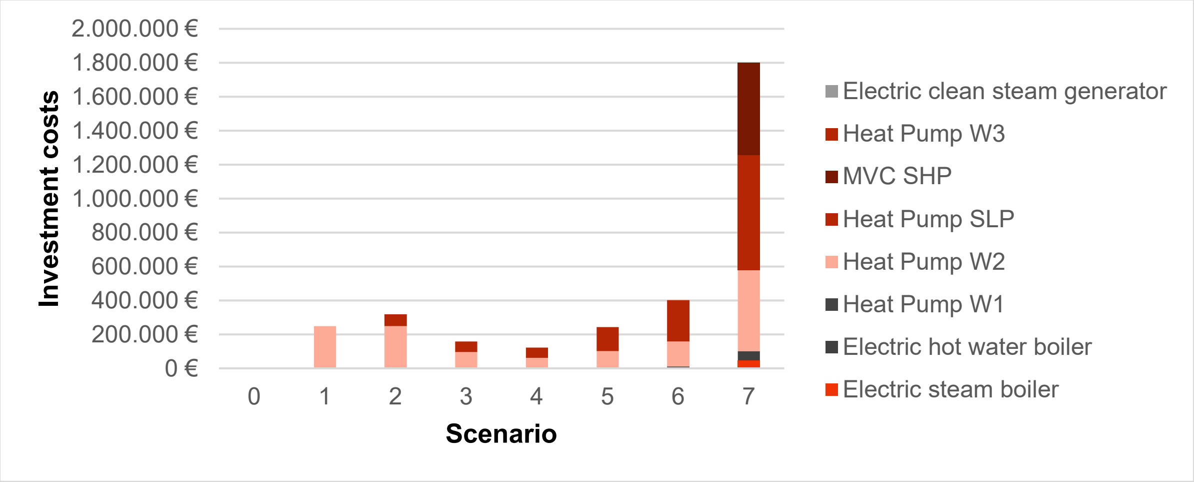

Figure 8: *Aggregate investment costs for all considered decarbonization scenarios.*

The investment costs for new conversion units only include equipment costs. Costs for installation and integration are not considered. Neither considered are costs for additional piping for new heat distribution systems or for the decarbonization measures at the process demand level since these costs are hard to estimate for an example case. Thus, costs presented in **Figure 8** need to be considered with care. Costs are dominated by hot water heat pumps that feed into hot water system W2 and for a steam generation heat pump (Heat Pump SLP). For Scenario 7, also significant costs arise for the vapour compression unit to produce high pressure steam (MVC SHP).

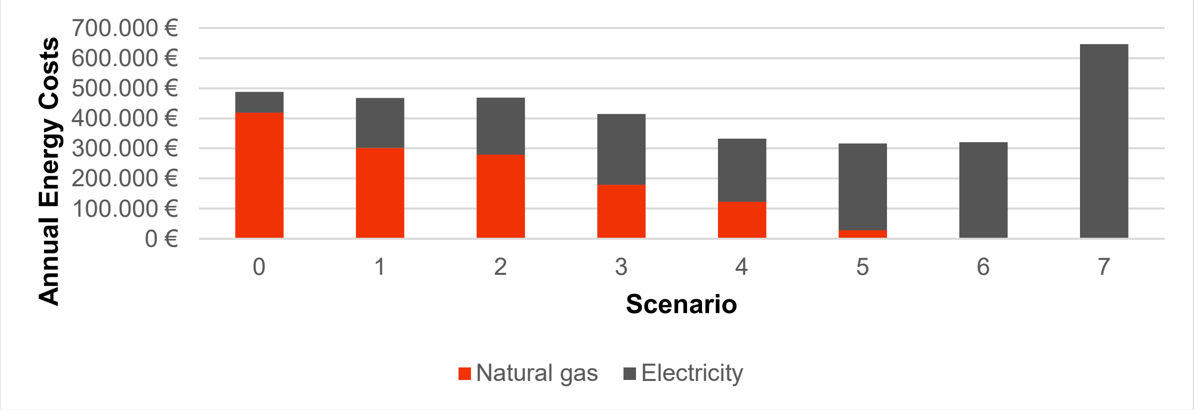

Figure 9: *Annual energy costs for all considered decarbonization scenarios.*

The annual energy costs for gas and electricity are shown in **Figure 9**. It is obvious that with an increasing number of decarbonization measures, primary energy consumption and even energy costs decline. This is due to the fact, that efficiency measures reduce the heating and cooling demands but also due to more efficient heat provision through low temperature heat distribution systems and the use of heat pumps.

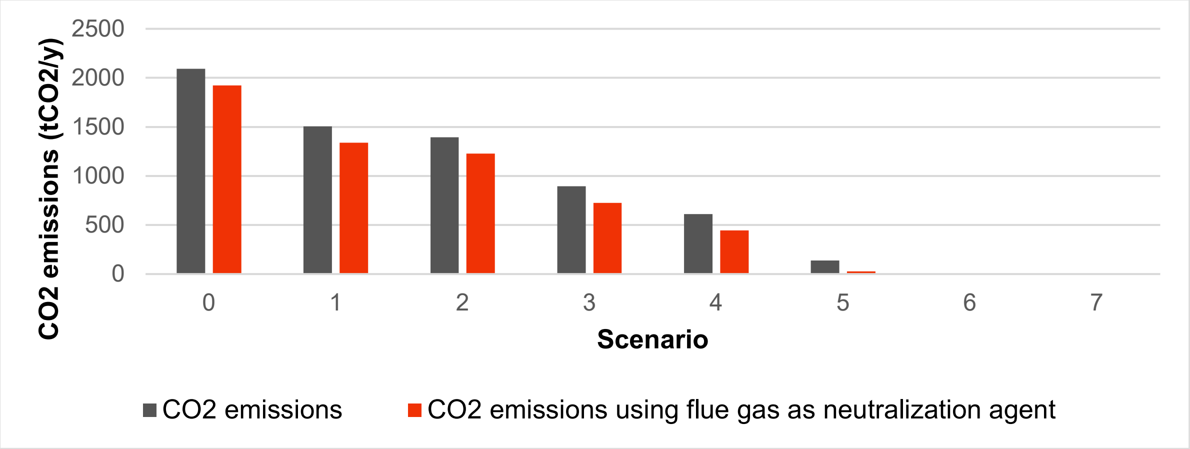

Figure 10: *CO_2 emissions for all considered decarbonization scenarios.*

Figure 10 shows that for scenarios 1-3 (level 1) a reduction in CO_2 emissions of 25% to more than 50% was obtained. Applying measures of level 2 (Scenario 4) increases the reduction of CO_2 emissions to roughly 75%. Allowing for membrane distillation for WFI production and adiabatic humidification for HVAC systems (Scenario 5) CO_2 emissions are reduced by 93%.

Another measure to further reduce CO_2 emissions is the use of state-of-the-art neutralisation facility employing CO_2 as agent. In these neutralization plants flue gases from fossil fuel-powered boilers are pumped through a column of wastewater tanks. This is usually done by a flue gas compressor to overcome the required pressure. After the reaction in the tanks the neutralised wastewater is disposed, and the residual flue gases are exhausted via the chimney. Based on feedback from plant operators we expect that around 8% of the total CO_2 emissions of a pharmaceutical plant can be extracted in the neutralisation facility when simultaneously neutralising the entire wastewater to a pH safe for disposable into the sewer. For this study a neutralisation process where wastewater enters the neutralisation facility with pH 12.5 and is disposed into the sewer with pH 9.5 was considered. Usually, this reduction would be achieved by using a mineral acid like e.g., sulphuric acid (H_2SO_4). In this scenario the use of 1 kg CO_2 as neutralising agent allows for a reduction of 0.97 kg in H_2SO_4 use. This reduction of mineral acid use directly leads to a reduction in emissions of sulphates into the wastewater that is disposed into the sewer and a decrease in operating cost.

4. Conclusion and Outlook

The results of this study show, that it is technically possible to transition to a net zero emissions energy system while reducing overall energy costs. However, if the heat distribution systems are not altered to make use of low temperature hot water systems combined with efficient heat pumps to supply suitable processes, and no measures are considered on the demand level, an increase in energy costs is inevitable considering todays energy costs. Furthermore, significant investment costs for new energy supply units go along with electrification of the current steam-heavy energy supply system, even if heat pumps are considered as a means of steam supply.

On the demand side, especially the use of efficient HVAC systems for air handling can drastically reduce both heating and cooling demands. Simulation results with a simple python model showed that, if all measures are fully exploited, cooling demands for HVAC units can be reduced by 94%, heating demands by 80% and steam demand by 71%. Another big change is the transition of distillation based WFI production to membrane systems that eliminate the demand for high pressure steam for WFI.

The results for this study are mainly based on technical feasibility. In the industry there are many regulatory issues that can arise with any change in processing equipment, especially on the demand side. Also, time consuming bookwork and process validation will occur whenever changes on level 2 (production related process parameters are altered) are considered. A change to membrane based WFI production is currently out of scope for many companies due to market restrictions for products incorporating this technology. These factors have been considered through the classification of decarbonization measures, but economic impact has not been fully assessed and strongly depends on the individual process and company.

Another uncertainty, that has not been fully addressed in this study is the costs for integration of the different decarbonization measures and for new units in the energy supply system. These costs are crucial for evaluating expected payback times of the suggested measures and need further investigation.

Data availability statement

All relevant parameters are stated in the paper. Time series used were generated based on these parameters or are referenced in the text. Time series for weather data were obtained from geosphere.at for station WIEN-DONAUFELD for 2021.

Author contributions

Conceptualization: AB; Methodology: AB; Software: TK, NN, AB; Validation: AB, MT; Formal Analysis: BM, AB, MT, FH; Investigation: AB; Data Curation: AB, DL, BM, MT, FH; Writing – Original Draft: AB, FH; Writing – Review & Editing: AB, MT; Visualization: VH, AB; Project Administration: AB; Funding Acquisition: AB, GDS

Competing interests

The authors declare that they have no competing interests.

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