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Title: Optimal Energy Supply Structures for Industrial Food Processing Sites in Different Countries Considering Energy Transitions

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Abstract

This study focuses on analysing the most energy efficient utility system supply structure in terms of carbon emissions, primary energy efficiency and energy costs. In the German food processing industry, the state-of-the-art technologies in the utility supply structure are a gas fired steam boiler for steam generation and ammonia chillers for chilled water generation. Low investment costs and its durability are attractive for industrial production sites. But, given the ongoing energy transition to renewable energy, opportunities to reduce emissions will become increasingly important. There are other energy supply options, such as Combined Heat and Power and Heat Pumps, that need to compete against the conventional energy supply systems. In the short-term, countries with presently high electricity Grid Emissions Factors (GEF) such as Germany and the USA, the use of decentralised CHP results in savings of primary energy and emissions. This option is less attractive for countries with already low GEF such as Norway. It is also less attractive in the long-term for countries like Germany as the on-going energy transition towards renewables is anticipated to decrease the current GEF by 50% in 2030. In these cases of low GEF, HP solutions provide the lowest emissions and highest primary energy efficiency.

Highlights

- Assessment of supply chains from energy source to final consumption
- Quantified environmental impact of process heat supply technology
- Analysed outlook for industrial energy supply structures in different countries
- With future low emissions electricity, heat pumps are a key energy supply solution

1. Introduction

The goal of 195 nations is to reduce the risks and impacts of climate change agreed by contract, of Paris world climate conference 2015. The main objectives of the agreement are to reach peak greenhouse gas (GHG) emissions by mid-century and holding the increase in the global average temperature below 2 °C above pre-industrial levels to address climate change. To reach these targets, all sectors, and especially the industrial sector, need to contribute to reducing GHG emissions by implementing energy efficiency measures at all stages of the energy conversion chain from generation to final consumption. As a result, over the next few decades, there will likely be a global pivot from heavy reliance on fossil fuels to the wide-spread uptake of renewable energy opportunities.

Country scale evaluations of emissions reduction options are useful for setting overall targets and informing Government policy. For example, Gerhardt [1] report that heat pumps (HP) are a key technology to decarbonise the residential and commercial heat energy market in Germany, whereas combined heat and power (CHP) is advantageous for industrial processes that need high temperatures and steam. Omid et al. [2] are investigating heat pump integration from a technical perspective in a slaughterhouse in Canada, Miah et al. [3] for a confectionery factory in the UK and Kapustenko et al. [4] for a cheese production in Ukraine. Walmsley et al. [5] reports about the appropriate placement of an open cycle heat pump in vapour recompression for the milk industry. Janghorban et al. [6] analysed for vapour-compression refrigeration and Shahandeh et al. [7] for distillation columns in methanol-water separation in detail the optimisation of heat pump integration in industrial processes. Hedegaard et al. [8] investigated the use of domestic heat pumps to store wind energy as hot water, linking the electricity and residential sectors. Meyers et al. [9] surveyed 249 companies of the food and beverage industry for lowering GHG emissions. They identified heat pumps and CHP as feasible solutions for emission reduction but focus only on today's status quo. Recent research papers focusing on the economic and ecologic impacts of broad-scale implementation of new technologies in Latvia [10], Saudi Arabia [11], UK [12], France [13] and Norway [14] are also reported. In other cases, studies have looked at assessing the energy and carbon emission savings by one or two technologies such as cogeneration [15], carbon capture and storage [16], or electrification [17] for an entire industrial sector. Other focus on national strategies for the whole power systems [18] for Portugal, UK, Brazil, China and the European Union [19] on ex-post data. However, such reports leave a gap between the overall national strategy and what are the realistic and economic solutions to implement at specific plants and sites. This paper attempts to connect high-level strategy with industry- and plant-level strategic action and implementation.

The food processing industry traditionally uses steam boilers and ammonia compression chilling machines for heat supply [20]. A common measure to decrease energy costs and increase energy efficiency is the application of gas engine CHP for heat supply [21]. Whereas heat pumps as an option for combined heat and cold are a currently discussed technically feasible option [4]. The aim of this paper is to investigate how the optimal energy supply structure for individual industrial sites, based on GHG emissions and primary energy consumption, varies between countries in 2015, 2020, and 2030. The optimal energy supply structure solution depends on a country’s available natural resources, primary energy factors, and electricity grid emissions factors, which determine the efficiency and environmental cost for providing final usable energy. In this way, national energy and emissions datasets for the present and projected future are linked to industrial plant data, to model the entire energy supply chain, from raw material through to refined energy, together with its associated emissions. Each industrial sector and each individual site have its own characteristic energy demand profile for process heat, chilled water, cooling water, and other utilities. The role of the energy supply structure is to convert natural resources, such as natural gas, to satisfy the required utility demands, e.g. steam. The impacts of the supply structure on cost and the environment are highly dependent on the energy source and the utilities used (i.e. Combined Heat and Power - CHP, Heat Pump - HP, Steam boiler).

This study reports the development of an EXCEL^{TM} spreadsheet tool for analysing individual industrial sites to determine the optimal energy supply structure in terms of primary energy use, GHG emissions, and/or energy costs. The analysis tool is applied to two case studies. One of a representative cheese factory model that has been validated against industrial data. Another one of a typical medium-sized meat processing plant with energy measurement data from an online energy monitoring system. The scope of the analysis includes looking at how the optimal energy supply structure changes for cheese factories located in Norway, France, and the USA. Ongoing efforts of these countries are taken into account by estimating current and future Emissions Factors (EF) and Primary Energy Factors (PEF) comparing the supply structure in Germany in the years 2015, 2020 and 2030.

2. Rating of Energy Systems

The selection of an energy source has an important impact on the ecological emissions and the primary energy efficiency of a site. The upstream chain that is defined by the supplier or his products leads to significant efficiency losses and emissions. Typical values of losses from the energy source to final energy are in the range of 10 to 70 %. Through the right choice, a company can directly influence the outcomes.

The first criterion is the extent of GHG emissions, which is summarised by a carbon dioxide equivalent (CO_2e). This criterion gives information about the environmental impact with specific reference to climate change.

The second criterion for comparison is the PEF, which is the ratio of the primary to the final energy. The advantageous of this measure is that it is a simple comparison and numerous data are readily available. The weakness of PEF is that it compares energy quantity at the same reference point, which is the Primary Energy, but does not consider energy costs, quality (e.g. exergy), and intensity, which characteristics of the energy source, i.e. the properties and potentials of natural gas, coal, uranium, hydro, wind energy, and solar differ.

3. An Elementary Understanding of Energy Systems in the Dairy Industry

Figure 1 shows the conversion routes from primary to useable energy and the extent to which suppliers and processing companies can influence it. Large industrial sites are usually supplied by the medium voltage power grid (e.g. 10 – 30 kV). The voltage gets reduced in a transformer station and distributed to the site grid. The main electricity consumers are electrical drives, approximately 80%. These can move solid bodies, pump liquids or compress gases. Further important applications are electronics and illumination [22]. Supplying heat by electrical energy is uncommon, but a possible option. Resistance heating for high temperature heating (e.g. electric steam generator) with low investment costs and low efficiency or heat pumps with high investment costs and high efficiency for low temperature heating are implementation options.

Resource supply structures for national electricity grids and the associated Grid Emissions Factors (GEF) differ for each country due to differences in geography, resources, and political drivers. Although the various regions of one country have stark differences in the supply system, a country is usually the most logical overall system boundary. Figure 2 shows the international comparison of PEF of electricity for the years 2015, 2020, and 2030 based on data from GEMIS (www.iinas.org). The corresponding GEFs are presented in Figure 3. The lowest emissions have power systems based on renewable or nuclear power. Austria, Swiss, France, Sweden and Norway are the countries with the lowest emissions as shown in Figure 3. Germany sits above the EU-27 average because of a high amount of coal power plants and the winding down of nuclear power. By 2030 Germany aims to reduce the 2015 GEF by 50% through good progress in the energy transition towards renewable energies.

Natural Gas remains an important energy source for supplying processes. It is used to supply steam, hot water, and hot air for production processes as well as a process feedstock. Utilities using fossil fuels produce heat with high temperatures and exergy. These are therefore too valuable to only use it for low temperature heating. CHP improves the exergy efficiency of using fossil fuels, particularly for low temperature heating applications. Natural gas is very good fuel in terms of emissions factor and primary energy efficiency as visualised as a dotted line in Figures 2 and 3.

In this paper, three conversion technologies on a company level are analysed. The separate conversion (SP) with boiler and compression chiller is the present industry standard. It comes along with unavoidable losses of thermal energy. In boilers, heat at a high temperature level is generated (above 1000 °C [23]) but only required in dairy processing for heating fluids to 50 – 140 °C, which leads to significant exergy destruction. Another significant loss is waste heat in the boiler exhaust. The exhaust temperatures are often >120 °C, which is well above the typical Pinch Temperatures for diary processes of 50 - 60 °C and, therefore, may be recovered through improved integration. Compression chillers normally reject heat to cooling towers. The working principal of those machines is to efficiently convert low temperature heat to above ambient temperature and then reject it to the environment. From this perspective, separate conversion, by its nature, contains significant heat and exergy losses that could be better utilised.

The CHP engine offers two heat sources. First the engine cooling at around 60 to 90 °C and second the exhaust fumes at temperatures of 270 – 680 °C after electricity generation. With an exhaust temperature of 270 °C, the quantum of heat in the exhaust and reject through engine cooling are similar [24]. Figure 4 shows a typical CHP engine unit. On the left is the generator driven by the piston gas engine. The engine is cooled by the grey heat exchanger, which is shown on the right-hand side of Figure 4. Manufacturer requirements have to be met for the condition and temperature of the return flow, which prevent the engine from overheating and undercooling, must be adhered to. The back pressure of the engine constrains the size of the exhaust heat exchanger, which means not all of the heat in the exhaust can be recovered. The permissible pressure drop is also manufacturer specification. In the example of Figure 4, the engine heat exchanger and the exhaust heat exchanger are connected. For dairy factories, the separate use of the two heat sources shows good integration potential dues the ability to generate hot water from the engine cooling and steam from the exhaust heat exchanger while also satisfying some of the electrical demands.

An important consideration for CHP engines is the temperature-enthalpy profile of the available heat, which is transferred to generate hot water and steam. Figure 5 compares possible exhaust profiles for CHP units from two different manufacturers. The thermal outputs of the CHP units in Figure 5A from lowest exhaust gas heat capacity flow rate to the highest one are 80, 109, 212, 374, 478 and 500 W/K. For the units in Figure 5B, the exhaust heat capacity flow rates are 81, 115, 207, 293, 549, and 660 W/K. An increase in the heat capacity flow rate often correlates with a decrease in exhaust gas temperature. Selection of the most appropriate CHP unit depends on the process heat demand profile for the industrial site.

Heat pumps can be utilised with a broad selection of refrigerants. Typical in the dairy industry is the use of ammonia for compression chillers that also can be applied in a two-stage open compression process as heat pumps [4]. The COP is determined using Equation 1. The isentropic efficiencies of both compressor stages are 0.7. The intermediate pressure level is calculated using Equation 2.

$$COP = \frac{Q_{evaporation} + Q_{condensing}}{W_{stage,1} + W_{Stage,2}} \tag{1}$$

$$p_{intermediate} = \sqrt{p_{condenser} \cdot p_{evaporater}} \tag{2}$$

In the dairy and the meat processing industry, typical evaporation temperatures are around -10 °C to deliver chilled water at 1 °C. Figure 6 represents the behaviour of the thermodynamic calculated COP for different condenser temperatures based on the stated compressor efficiencies. Dependent on the level of the requested process heat, there are large differences in the efficiency of the heat pump. The lower the required temperature lift across the heat pump is desirable to maximise the COP. Appropriate matching of heat pump system to process heat demand profiles is, therefore, critical to reducing electricity consumption.

CHP and heat pumps both need low temperature heat sinks for reaching high efficiency. Industries with low temperature heat usage, such as the dairy and food processing sector, are well suited for integration of these technologies.

4. Methods

The GEMIS database provides emission and primary energy factors for natural gas and electricity. The values for natural gas are constant for all countries and future scenarios. The quantum of emissions associated with the pre-production of natural gas is very low compared to the emissions caused by burning it. An increasing efficiency in the preproduction has minimal impact on emission and primary energy factors. Emission and primary energy factors for electricity are highly dependent on the individual country due to significant differences in the share of renewables, nuclear power, gas, and oil power plants. Many nations are in the progress of increasing the share of renewables while also increasing energy efficiency, which impacts the framework conditions for industrial energy supply structures. For the future scenarios, data estimates are extracted from GEMIS. For non-EU countries, data from the International Energy Agency (IEA) Energy Statistics Database are utilised. For EU countries (except Germany), the scenarios are based on the European

Policies to Promote Sustainable Consumption Patterns (EUPOPP). Germany's future national energy supply structure is predicted by [25], who reports on a pilot study of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMU). The primary energy Eq. (3) and the CO_2-emissions Eq. (4) are calculated by multiplying the country-specific factors PEF and GEF with the accumulated final energy demand of each utility.

$$E_{Primary} = PEF \cdot E_{final} \tag{3}$$

$$GHG_{emissions} = GEF \cdot E_{final} \tag{4}$$

To determine the final energy on the plant level performance, equations for a variety of utility supply systems for individual sites, together with their assumptions, are presented in Table 1. The steam boiler provides steam for the processes and heats the process water. In the scenarios with HP and CHP, the steam boiler covers the peak loads. The compression chiller supplies the system with cold water. For both supply systems with HP and CHP, the determination of the final energy demand is more complex compared to the conventional separate energy conversion. The HP operates as a heating unit if the cooling demand equals zero. In the regular cases with a cooling load, the operating point is controlled by the cooling demand. The heat of the HP is used for providing hot water. If a surplus of heat occurs, it is cooled via a cooling tower. The CHP unit supplies steam, hot water, and electricity. The electricity production of the unit is controlled by the maximum heating demand for steam and hot water. If the CHP unit only needs to provide 50% of its maximum thermal output, the electricity output is also reduced to 50%. This control ensures the unit operates at maximum efficiency. Any surplus steam provided by the CHP is used to heat the hot water system. In this case, the ratio between the supply of hot water and the amount of produced steam is limited to 43% because the engine cooling must be ensured. If the demand for steam is lower than 43% of the hot water demand, the final energy of the CHP units is determined by those two demands and the efficiency. In cases of a higher steam demand, the supply of thermal energy by the CHP is limited to satisfying the hot water demand The lack of CHP-steam compared to the actual demand is covered by the steam boiler.

The calculations are stationary and the utilities work with a constant efficiency and their output fit the demand in the most efficient way. The analysis focuses on the comparison of the CO_2 emissions and primary energy of the different supply structures in the years 2015, 2020 and 2030.

Figure 7 shows the graphical user interface of the spreadsheet tool. The energy flow is modelled from the sources to the sink. There are two public conversion paths that are possible: natural gas (grey) and electricity (yellow). From there, energy conversion occurs at an individual industrial site level. To provide steam (purple), hot water (red), electricity and chilled water (light blue), the three mentioned conversion paths are possible. The top flow chart is for CHP, the middle is for heat pumps, and the bottom is for separate conversion. Primary energy savings are visualised in green and carbon emissions in dark blue. In the circle on the right-hand side, energy consumption costs are quantified. Required input cells are clearly labelled. Drop-down menus have been implemented to select the investigated country (18 possible countries) and year (2015, 2020, or 2030). Inputted values are then used in separate sheets that contain the numerical models and formulas relating to the three investigated energy supply structures. Results are summarised using the three flow charts.

5. Cheese Factory Case Study

5.1 Background

The evaluation of the tool applied to a cheese factory case study that processes 1 ML/d of raw milk. The milk is transported from the farms in a refrigerated milk truck to the dairy factory. If the temperature at the reception exceeds 6 °C, it is cooled before storing. Before processing, the milk is pasteurised (e. g. 10 s at 74 °C) and fractionated using centrifugal separation and ultrafiltration to whole milk, skim milk, cream, and milk protein concentrate. In a parallel process, the taste giving bacteria is cultured in sterilised skim milk. These components are mixed in vats according to specific recipes, standardised by fat and/or protein content, and matured by bacteria culture. From the vat, milk crud is manufactured and the whey is drained after multiple cutting processes. From this point, the curd is pressed and shaped to form a cheese block. The final steps are brine salting and storage for further maturing [26]. All these processes demand energy. In the case study, three different technologies for this task are compared: Separate conversion (SP) of heat and power (grid), CHP engine with natural gas and heat pumps (HP) using grid electricity. A detailed process Pinch Analysis has been carried out to provide the necessary utility demand data in Table 2.

Process heating and cooling are supplied at three levels: steam at 4 bar (144 °C), hot water at 75 °C, and chilled water at 1 °C. The Grand Composite Curve (GCC) in Figure 8 shows the utility demands for the cheese factory. The COPs for a compression chiller and a two-stage ammonia heat pump are calculated by a MATLAB® Model using the CoolProp library [27]. Efficiencies of CHP [24] and furnace [28] are taken from literature. The price for electricity for the analysed dairy plant in Germany is 80 €/MWh and for natural gas 38 €/MWh [29] with an assumed annual price increase for electricity of 3 % and for gas of 5 %.

5.2 Optimal Energy Supply Structures for the Cheese Factory Case Study

The development of the optimal energy supply structures for the cheese factory case study looked at the impact of its physical location (Germany, Norway, France, and the USA) and how the ongoing energy transition (2015, 2020, and 2030) affects the optimisation. Figure 9 shows the comparison of locating a cheese factory in Norway, a country with a large share of renewable energies, France with a majority of nuclear power, and the USA with a fossil fuel based system.

As expected heat pumps have a major advantage if a country's electricity system has a low GEF and high efficiency. Since the primary energy efficiency of renewables is higher than the one of nuclear power, HP in Norway leads in all categories. In France, HPs can significantly decrease CO_2 emissions but have a negative impact on primary energy efficiency. In the USA and Germany, CHP is in all categories preferable because they have low primary energy efficiency and high GEFs. Figure 10 shows how the performance of various energy supply structures is affected by the energy transition. It indicates that CHP is, in the case of emissions, only one life cycle away from being the highest emitting energy supply structure. It is expected by 2030 that HPs, which are currently unfavourable, will become the best technology in terms of GHG emissions and cost effective for a cheese factory in Germany.

5.3 Sensitivity Analysis of the Cheese Factory Case Study

With the sensitivity analysis, the results are more generalised. When interpreting these diagrams, it must be considered that the results apply specifically to the heat loads and parameters in Table 2, which are for a current Cheese factory in Germany. However, through the sensitivity analysis, the results may more generally apply to the dairy sector because the various dairy processes use similar temperature levels of heating and cooling.

Figure 11 shows the impact of GEF on the total GHG emissions that result from energy usage. Since CHP in this use case is depended on natural gas, the impact of GEF is low on the GHG emissions. Heat pumps and separate conversion show stronger gradients due to a higher share of required electricity consumption. The points of intersection are the technology crossover points with respect to GHG emissions. In energy systems with a GEF lower than 545 gCO_2/kWh, heat pumps result in fewer emissions than separate conversion. If the grid emissions are less than 380 gCO_2/kWh, heat pumps are then preferable over CHP.

The steep gradient for GHG emissions from HPs is an advantage. As more renewable energy is added to the national grids through the energy transition period, HP emissions decrease drastically due to the rapid decline in GEF. Heat pumps for industrial process heat are, therefore, positively enhance the energy conversion supply chain when considering the current and future energy transition.

Figure 12 shows the sensitivity analysis from a cost perspective. For calculating the ratio for electricity to natural gas prices, a base price of natural gas of 0.035 €/kWh the assumption of stable natural gas prices.

6. Meat Processing Case Study

6.1 Background

A second case study is carried out for a meat processing factory. The data is from a medium size plant located in Germany that produces raw, cooked and boiled sausages. The analysed company produces around 1,200 t/y of meat. The supplied raw materials are cut and stored cold. The main production process starts with the cutter and/or meat grinder where the recipe is blended. The sausages are boiled or cooked and then matured or directly cooled before storage. The raw sausages are aged for a specific combination of holding time, temperature and humidity depending on the type and flavour of sausage. The next step is the cooling of the product followed by packing and delivery. The energy supply structures of SP, CHP and HP, the same three technologies, are compared. Measurement data have been retrieved from the plant's online energy monitoring system to perform a detailed process Pinch Analysis. The results are shown in Figure 13 and the necessary utility data are listed in Table 3.

Process heating and cooling utilities are supplied at four levels: (1) low temperature (LT) freezing at -15 °C, (2) cooling water at 23 °C, (3) hot water system at 60 °C, and (4) steam at 12 bar (187 °C). The GCC in Figure 13 shows the integration points and demands for each utility. In general, the loads are nearly ten times smaller compared to the cheese factory. Due to the lower temperature lift of the HP, a single-stage heat pump is applied. The efficiencies of the utilities are calculated the same way as in the first case study. Energy prices and price increases are set to the same values to ensure comparability.

6.2 Optimal Energy Supply Structures for the Meat Processing Case Study

The evaluation of the GCC shows that approximately one-third of fuel can be substituted by electricity. All hot water demand can be generated through the CHP unit and the steam can be partly substituted. The amount of steam substitution is dependent on the heat potential from the exhaust. The CHP unit is intentionally sized to maximize efficiency which means for this case additional steam is needed from a boiler. This leads to a higher basic amount of fuel applied compared to the cheese factory case study. Figure 14 shows the results of the primary energy and carbon emission analysis. Again, HP is the favourable technology in Norway and France from an emissions perspective. In the USA, the preferred technology changes. In the first case study, CHP, SP followed by HP is the order of preference. CHP is still the best option but HP is the second best energy supply option in terms of both primary energy use and GHG-emissions. This change is caused by the lower processing temperatures in meat processing compared to the cheese factory such that the COP of the HPs significantly increases. The balance between cooling and heating demands also supports the use of HPs, leading to a low heat rejection rate to the environment.

Figure 15 shows those advantages on the time-related development in Germany. The high efficient heat pump in 2020 will be the most emissions friendly utility of the three considered technologies.

6.3 Sensitivity Analysis of the Meat Processing Case Study

Figure 16 shows the impact of GEF on the total GHG emissions that result from energy usage. Compared to the cheese factory case study the intersection has moved down and to a single point at 320 g/kWh. Below this value, HP is favourable above CHP. Due to the difference in process heat demand and integration, the gradient for the HP is lower, meaning the system and, therefore, its performance is less sensitive to the energy transition.

Figure 17 shows the sensitivity analysis from a cost perspective. The methodology is the same as for the cheese factory case study. Below a ratio of 1.4, the heat pump is preferable whereas, above 1.4, CHP is better. Separate conversion is not the most economically favourable for all the considered scenarios for meat processing.

7. Generalisation of Results to the Food Processing Industry

Both case studies show a preferential integration of HPs in the future as a way to help reduce emissions and PEF (depending on the country). When comparing the cheese and the meat processing factory, the results show a strong influence of the plant's thermal energy profile on the utilities primary energy usage and GHG-emissions. The GCC of the Pinch Analysis provides a thermodynamic basis for quickly determining and comparing various energy supply structures for a plant. In general, a flat profile with a pinch temperature in the range of 10 to 60 °C as well as a low temperature difference between cooling and heating utilities are good indicators for favourable integration of HPs. Processes that fit this energy demand description that has been reported in the literature include milk drying [30], vegetable oil processing [31] and a slaughterhouse [32]. For the economical implementation of heat pumps for process heat, low electricity prices are necessary. The economic potential is, therefore, currently low in many countries.

8. General Usage of Results in Legislation and Energy Economics

This section describes questions that appear during an energy transitions process towards renewable energies. Germany is at the beginning of this process that has multidisciplinary scientific issues. In this paper, possible options for cleaner production and technologies are described. For implementation, proactive planning is necessary that needs the right balance between regulation and economics.

Forecasts of energy prices are uncertain but Government regulation can have a significant influence, which in turn impacts on the selections made at the industrial plant level with respect to the energy conversion technology. At present, a large share of industries in Germany and other industrial nations is free of any renewable energy levy. This has resulted in the ratio of electricity to natural gas being between 2 and 3. Recent public debate has focused on how to involve industry in the costs of the energy transition. Higher electricity prices due to the costly energy transition, however, would appear to drive industry away from low GHG-emissions solutions, e.g. HPs, and towards higher emissions options, e.g. CHP, due to poor policy and price signals. The national goal of decreasing carbon emissions by the energy transition is in conflict with the financially preferential downstream energy conversion technology within the energy supply chain. This is an important factor because 21 % [33] of final energy use in Germany is process heat demand. Industrial energy utilities have lifetimes of around twenty years. There is now the chance to prevent technology lock-in effects.

The results can also apply to hybrid-utility-systems (e.g. CHP and HP) when buying electricity with variable prices. In times with low energy prices, a high amount of variable renewable energies (VRE) are in the system. Therefore, GEF is low, which favours the use of heat pumps. When prices on the spot market are high, CHP is preferable in terms of ecological and economic figures. The intersection point between the technologies could be used to develop the control strategies to switch between natural gas and renewable energies to minimise GHG-emissions. Today, business models in Germany can be developed on a day-ahead, intraday or control power market.

9. Conclusions

A spreadsheet tool has been successfully constructed to analyse and optimise energy supply structures for individual industrial sites. This site level analysis is intended to be part of many improvements throughout the entire energy supply chain. Case studies for a cheese factory and meat processing plant show the site location and the long-term view of the make-up of national energy systems greatly affect the performance and preference of implementing different energy supply technologies, such as Combined Heat and Power, Steam boilers, and Heat Pumps. The constructed spreadsheet tool requires basic parameters that describe a factory’s energy demand for each medium. Pinch Analysis links into the tool by providing targets for utility demand. A sensitivity analysis has been carried out to generalise the results. It shows that heat pumps can accelerate the energy transition process at the downstream side to minimise GHG emissions. To prevent technology lock-in effects in countries such as Germany, Government regulation is necessary. Hybrid-utility-systems are a market driven alternative in energy systems with a large share of variable renewable energies.

In the cheese manufacturing case study heat pumps are the preferred option when the GEF is lower than 380 g/kWh. With higher GEFs it will be CHP. In terms of costs the threshold value is at a ratio of 1.6 from electricity to fuel costs. In the meat processing case study those values are lowered to a GEF of 320 g/kWh and a ratio of power to fuel costs of 1.4. Summarised between 32 and 52% GHG emissions can be saved in German dairy and meat processing between 2015 to 2030 choosing heat pumps as technology for heat supply. At present, the developed tool is limited and will be the subject of future work. It currently provides only a static analysis. Further investigations will be taken with a dynamic MATLAB®/Simulink® model respecting process heat load curves, electricity demand and weather dependency. Furthermore, extensions to a higher variety of primary energy inputs (e.g. biomass) and energy supply systems (e.g. combined cycle gas turbine) suited for the chemical and heavy industries (e.g. oil refining and steel making) are planned as part of on-going research.

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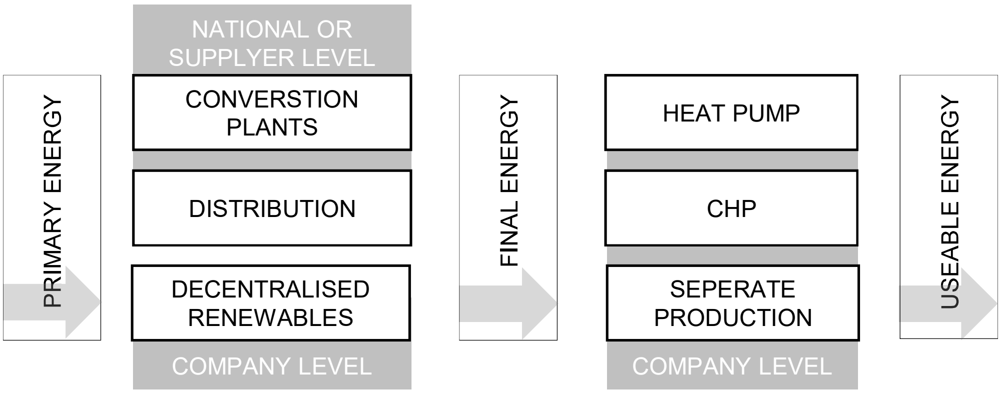

Figure 1: Conversion pathway of natural resources (Primary Energy) into Useable Energy.

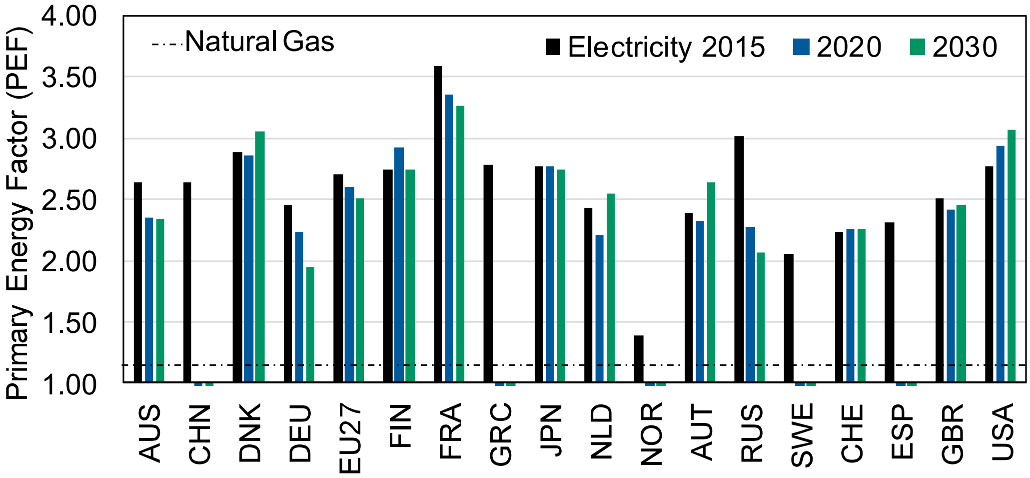

Figure 2: Primary Energy Factors for various countries in 2015, 2020, and 2030 (Data from GEMIS).

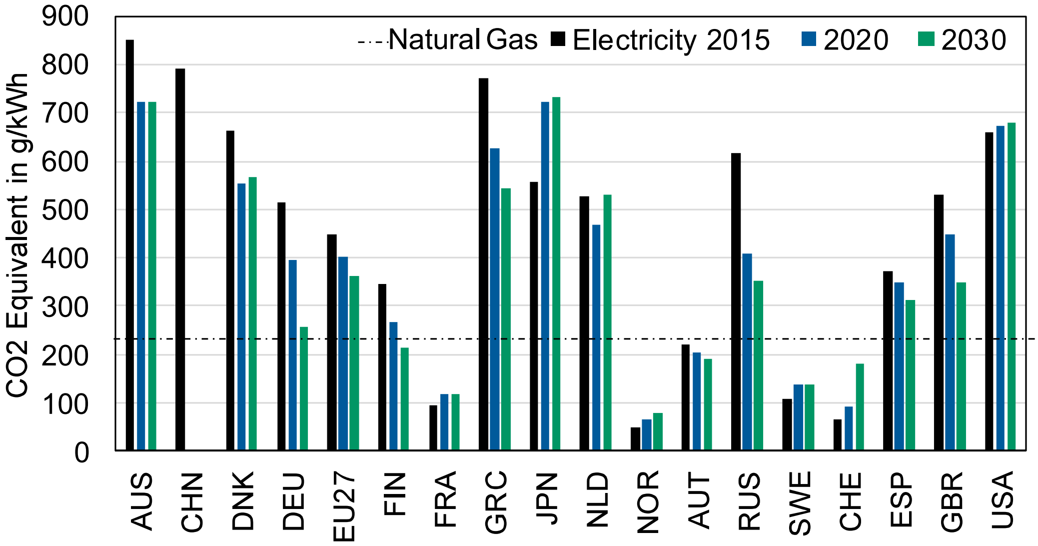

Figure 3: Grid Emissions Factors for various countries in 2015, 2020, and 2030 (Data from GEMIS).

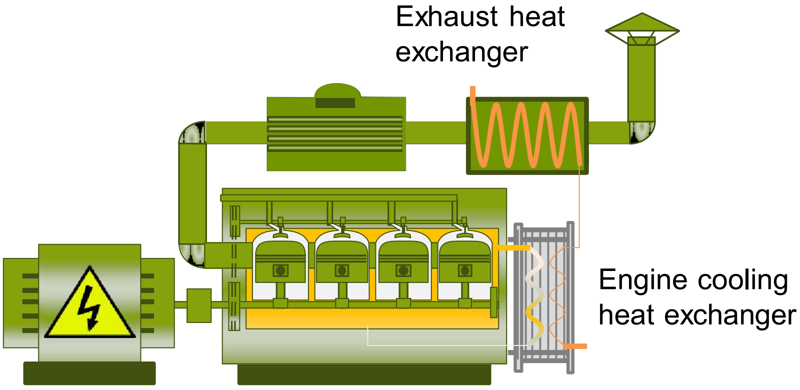

Figure 4: CHP engine with heat sources of engine cooling and exhaust heat usage [34].

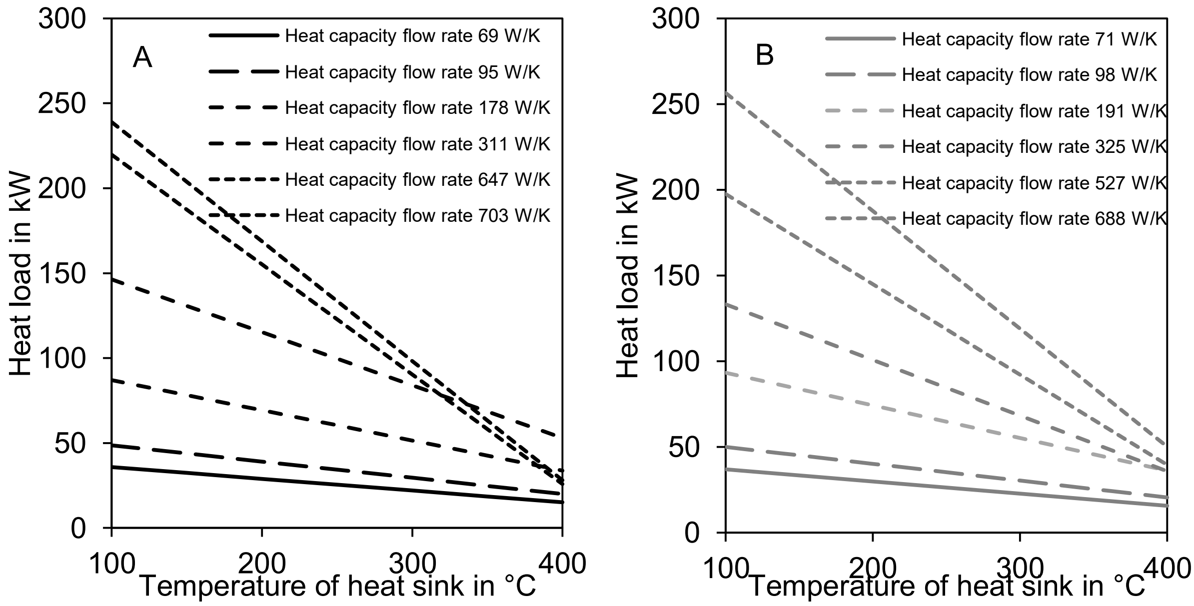

Figure 5: Possible heat from CHP engine exhaust depending on temperature level, heat capacity flow rate and manufacturer.

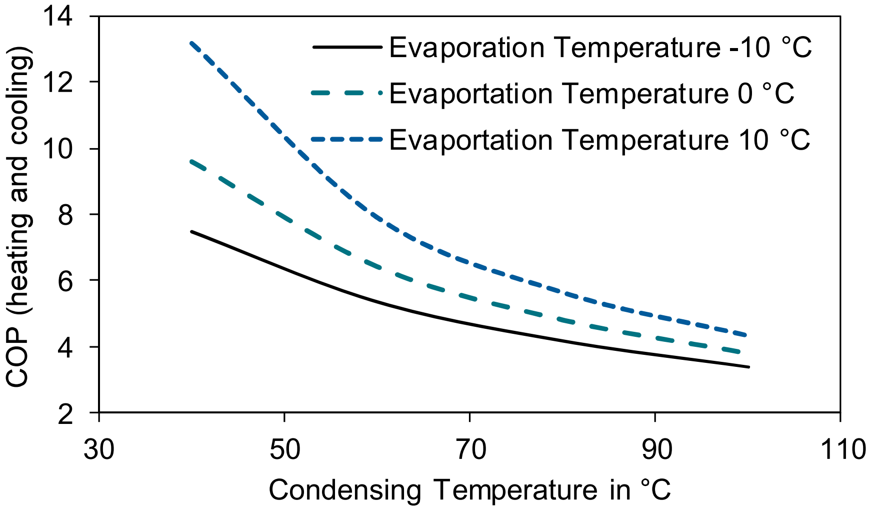

Figure 6: Thermodynamic COP of a two-stage ammonia heat pump.

Table 1: Utility supply options using natural gas and electricity.

Utility	Equation	Condition	Assumptions
Steam Boiler	$E_{natural\,gas} = \frac{E_{hot\,water} + E_{steam}}{\eta_{steam\ boiler}}$	None	• Peak load boiler • Steam to hot water
Compression Chiller	$E_{electricity} = \frac{E_{cold}}{COP_{chiller}}$	None	
Heat Pump	$E_{electricity} = \frac{2 \cdot E_{cold}}{COP_{hp\,heat} + COP_{hp\,cold} - 1}$	$E_{cold} > 0$	• Demand for cold energy determines heat pump power •Heat surplus to cooling tower
	$E_{electricity} = \frac{E_{hot\,water}}{COP_{hp\,heat}}$	$E_{cold} = 0$	
Combined Heat and Power	$E_{natural\,gas} = \frac{E_{hot\,water}}{\eta_{CHP\,thermal}}$ $E_{electricity} = -E_{hot\,water} \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} = 0$	• Heat demand controlled electricity production • Max. steam – hot water ratio 43% (3/7) • Surplus steam to hot water
	$E_{natural\,gas} = \frac{E_{hot\,water} + E_{steam}}{\eta_{CHP\,thermal}}$ $E_{electricity} = -(E_{hot\,water} + E_{steam}) \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} < E_{hot\,water} \cdot \frac{3}{7}$	
	$E_{natural\,gas} = \frac{E_{hot\,water} + E_{hot\,water} \cdot \frac{3}{7}}{\eta_{CHP\,thermal}}$ $E_{electricity} = -(E_{hot\,water} + E_{hot\,water} \cdot \frac{3}{7}) \cdot \frac{W_{el,CHP}}{Q_{th,CHP}}$	$E_{steam} \geq E_{hot\,water} \cdot \frac{3}{7}$	

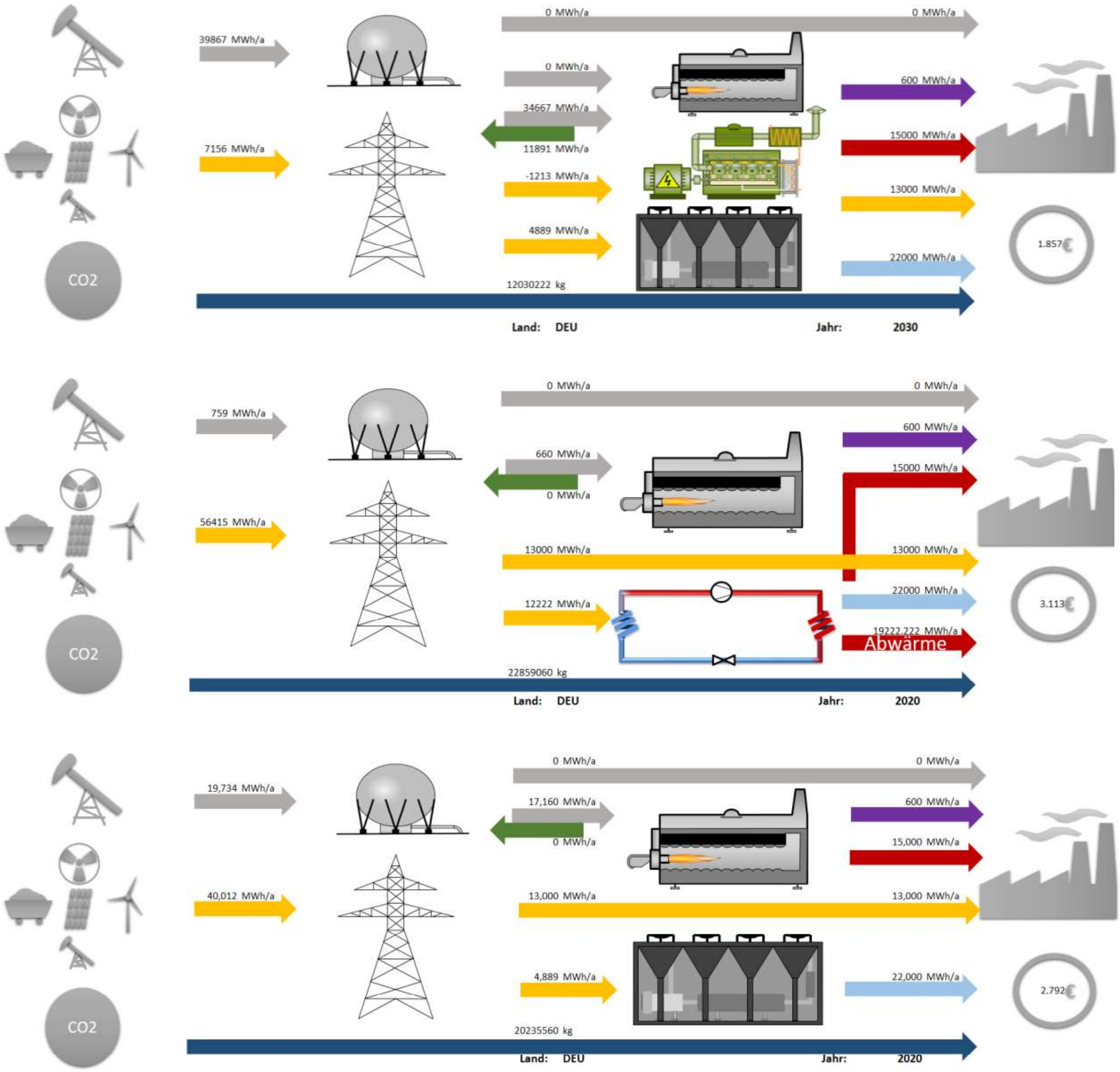

Figure 7: Graphical user interface of the excel spreadsheet for CHP, heat pump and separate conversion (Top down from above).

Table 2: Input parameters for the model with measurement data from a German cheese factory. Supplemented with own calculations.

Loads of Factory	Value	Unit	Efficiency of Utilities	Value
Hot water	15,000	MWh/y	CHP Efficiency thermal	0.45
Steam	600	MWh/y	CHP Efficiency electricity	0.41
Electricity	13,000	MWh/y	CHP coefficient	0.91
Ice water	22,000	MWh/y	Efficiency of thermal reference	0.9
Total	50,600	MWh/y	COP Compression chilling machine	4.5
			COP heat pump heating	2.6
			COP heat pump cooling	2.0
			Furnace efficiency factor	0.9

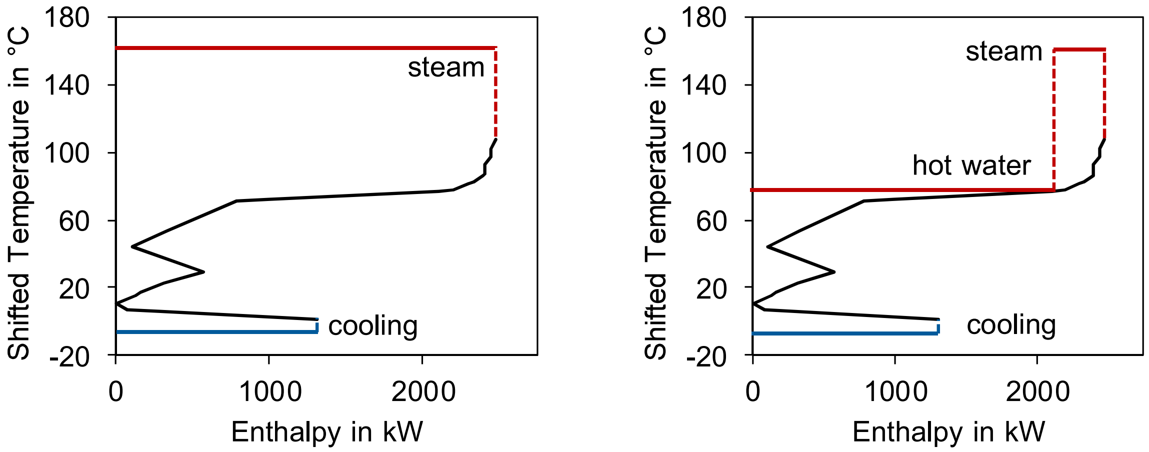

Figure 8: GCC of a cheese factory with integration points of utilities. Left integration of separate conversion. Right integration of CHP and HP by an extra hot water supply.

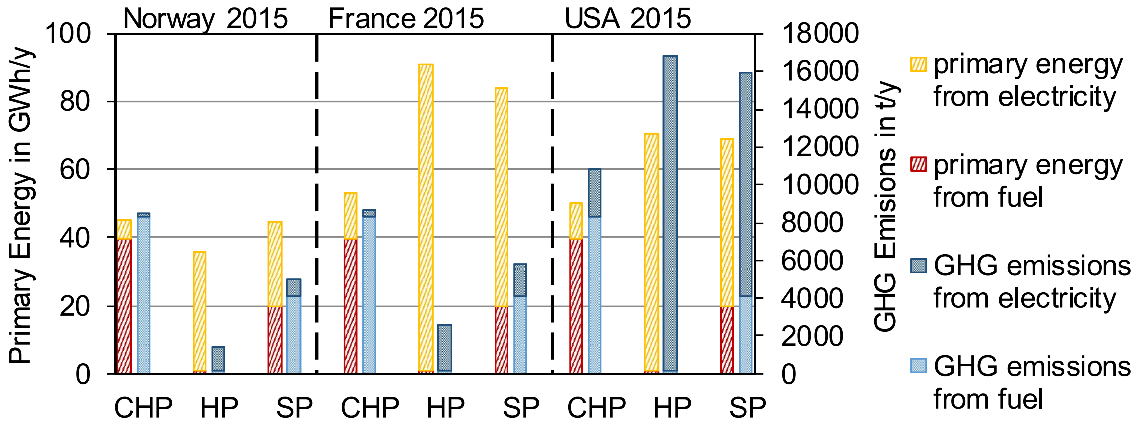

Figure 9: Comparison locating a cheese factory of Norway, France, and the USA on the performance of various energy supply structures in 2015.

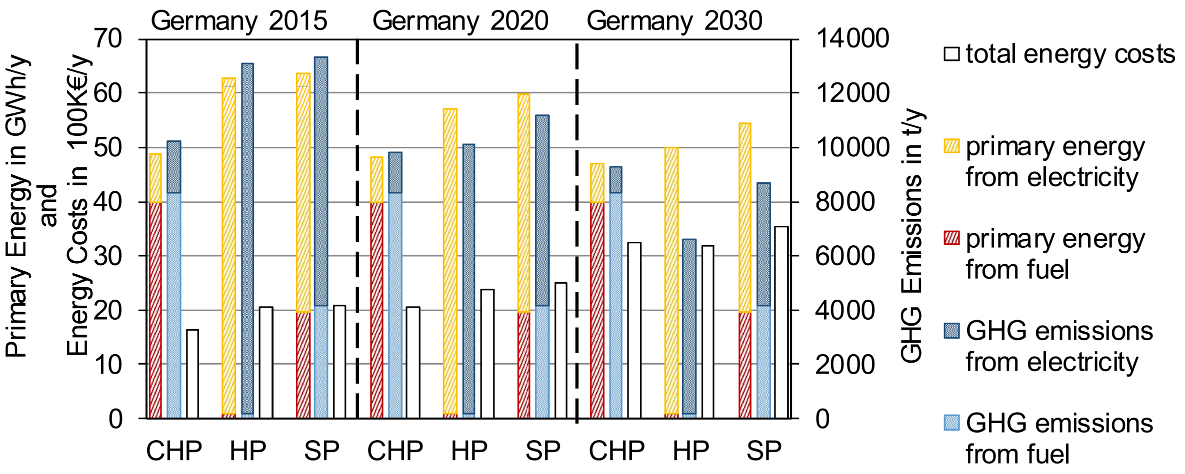

Figure 10: Influence of energy transition on a cheese factory in Germany for 2015, 2020, and 2030 including fossil fuel based systems.

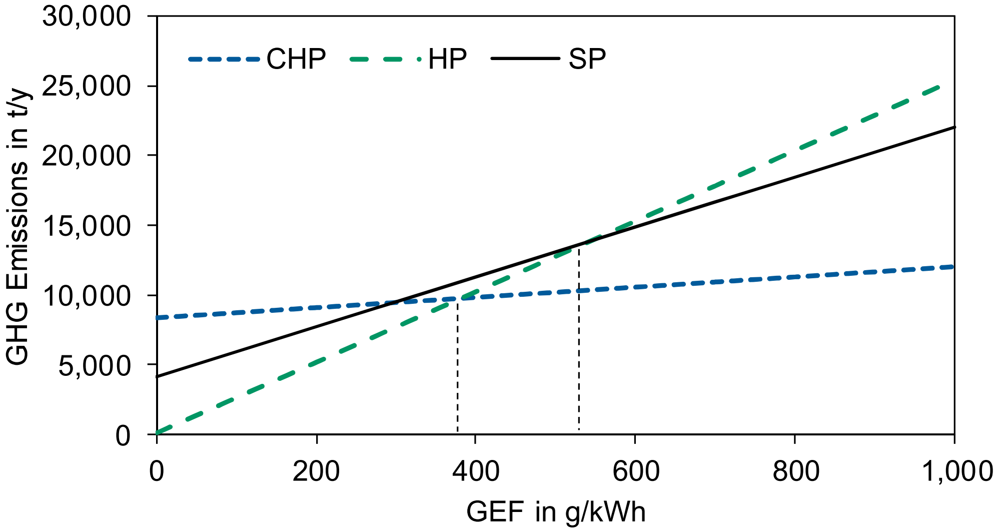

Figure 11: Sensitivity analysis of GHG-emissions for the cheese factory case study.

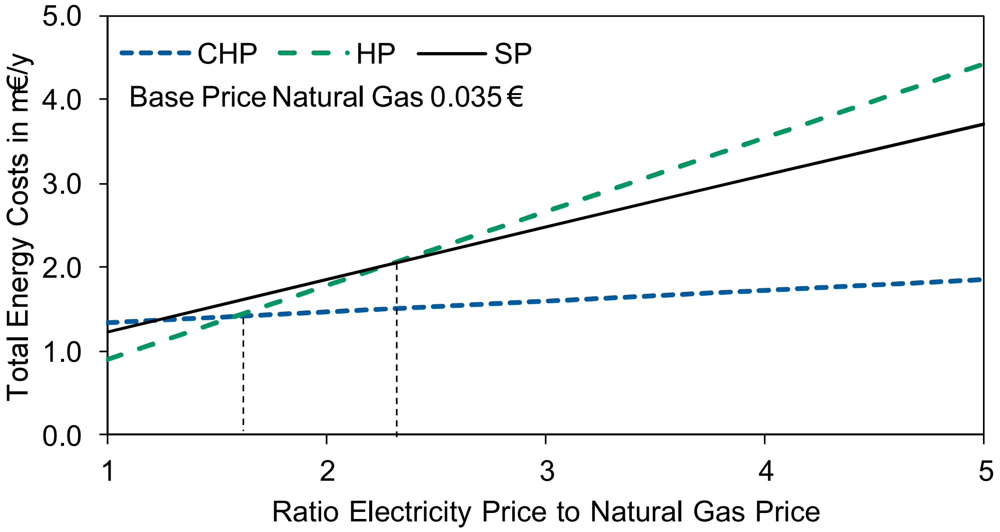

Figure 12: Sensitivity analysis of Total Energy Costs for the cheese factory case study.

Table 3: Input parameters for the model with measurement data from a German meat processing plant. Supplemented with own calculations.

Loads of Factory	Value	Unit	Efficiency of Utilities	Value
Hot water	526	MWh/y	CHP Efficiency thermal	0.45
Steam	1,228	MWh/y	CHP Efficiency electricity	0.41
Electricity	1,336	MWh/y	CHP coefficient	0.91
Ice water	1,101	MWh/y	Efficiency of thermal reference	0.9
Total	4,191	MWh/y	COP Compression chilling machine	4.5
			COP heat pump heating	4.4
			COP heat pump cooling	5.4
			Furnace efficiency factor	0.9

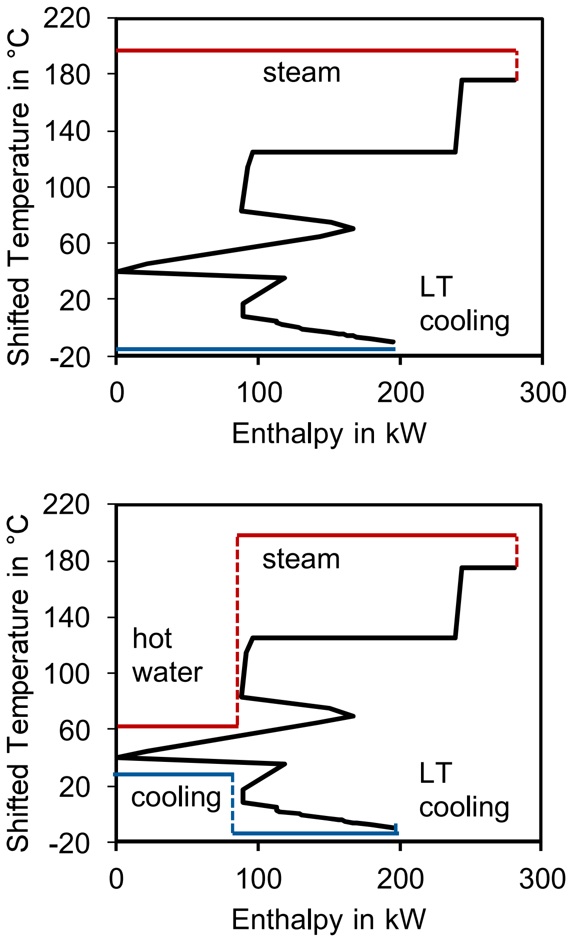

Figure 13: GCC of a meat-processing factory with integration points of utilities. Left integration of separate conversion. Right integration of CHP and HP by an extra hot water supply.

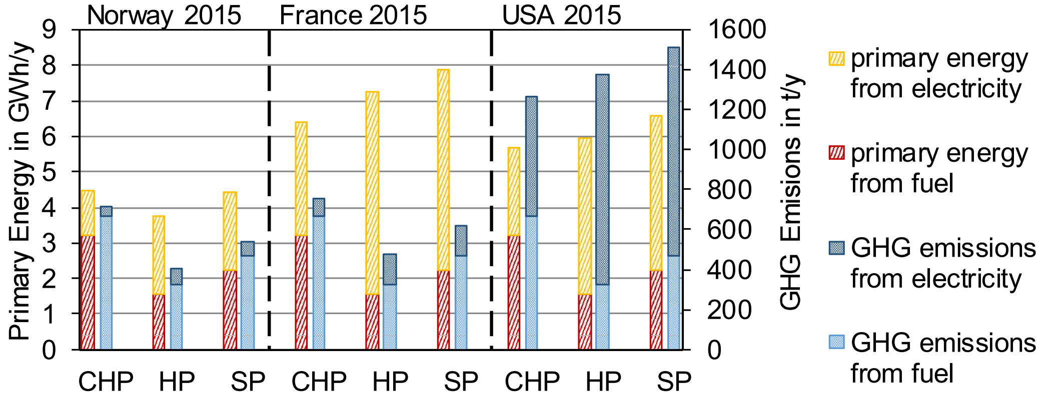

Figure 14: Comparison locating a meat-processing factory of Norway, France, and the USA on the performance of various energy supply structures in 2015.

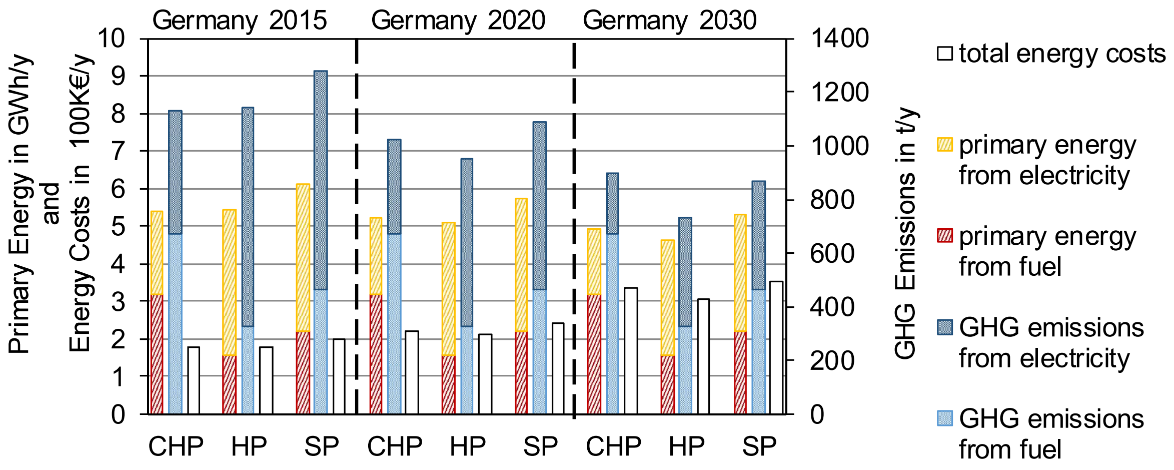

Figure 15: Influence of energy transition on a meat-processing factory in Germany for 2015, 2020, and 2030 including fossil fuel based systems.

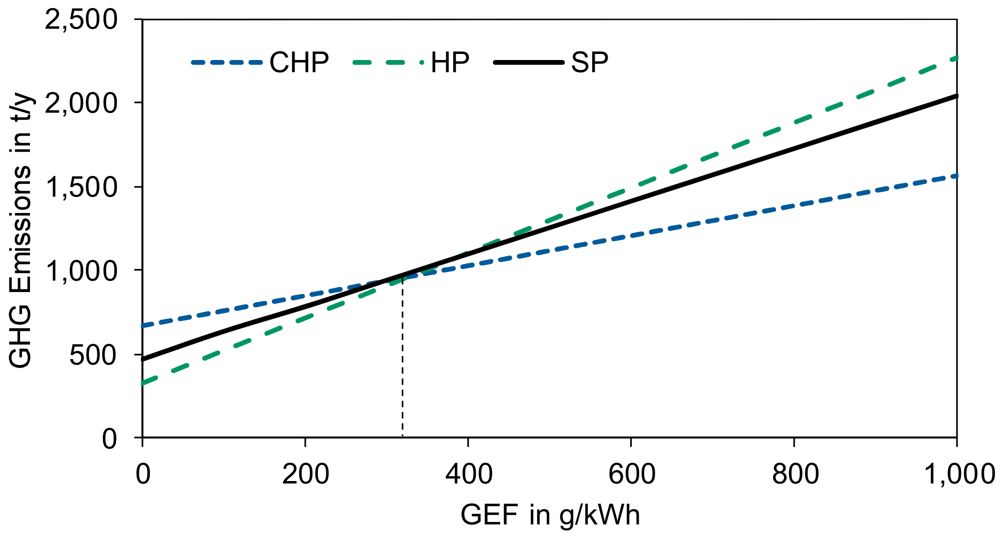

Figure 16: Sensitivity analysis of GHG Emissions for the meat processing case study.

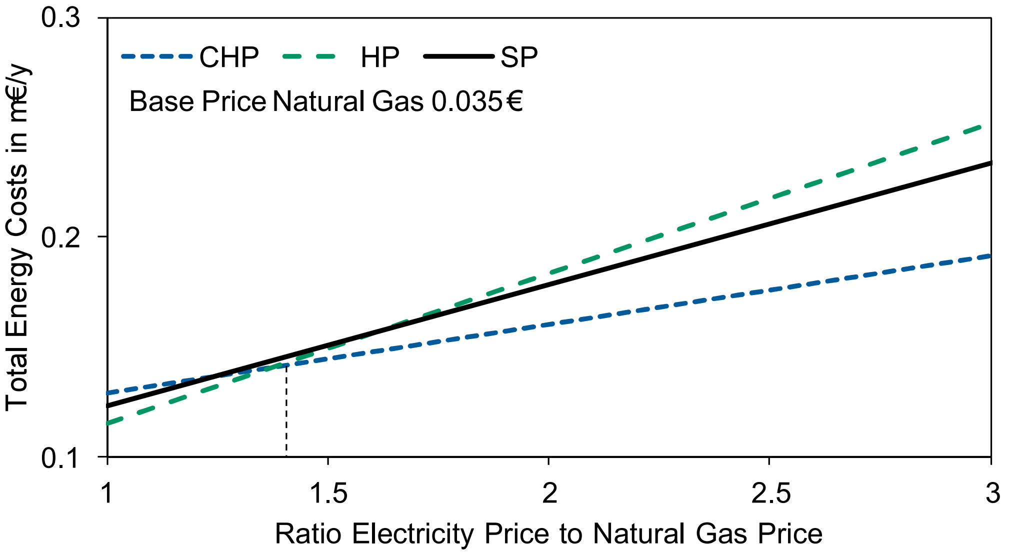

Figure 17: Sensitivity analysis of Total Energy Costs for the meat processing case study.