

Multisectorial Energy Integration of Low-Temperature Brewery Process, Manufacturing Industry and District Heating Network

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ABSTRACT

Low-temperature industrial processes release substantial amounts of waste heat, representing a largely untapped renewable energy resource. This study focuses on the brewery sector, encompassing both beer and whiskey production, along with its integration with manufacturing and city. The brewery industry generates approximately 0.061 kWh of waste heat per liter of beer, while whiskey production releases around 2.2 kWh per liter, with most of this waste heat available at temperatures close to 95 °C. Such low-grade heat is well suited to meet heating demands in manufacturing industries and urban district heating networks, where temperature requirements typically remain below 80 °C. Multiple technological options for meeting process heat requirements and recovering waste heat are evaluated using the OSMOSE energy integration framework. The study assesses the technical performance and economic viability of these options under varying assumptions for electricity prices, natural gas prices, and carbon pricing. Depending on market conditions, overall external utilities consumption reductions ranging from 22% to 63% are achieved. Price of utilities also has an effect on reduction of emission, as it is ranging from 25% to 90%. The results highlight the significant potential for cross-sectoral heat integration between breweries, manufacturing industries, and urban energy systems. A comparison is drawn between a case in which 5 th generation system (case 1) is activated and a case in which 5 th generation is not active (case 2). It was observed in most of the market conditions, case 1 is energetically, environmentally and economically more sustainable compared to case 2. In one of the market condition it was possible for both the cases to be energetically a carbon negative solution as it was economically feasible to capture biogenic CO₂. The work helps in validating that strategic waste heat recovery and utilization can substantially enhance energy efficiency, support industrial decarbonization pathways, and improve the resilience of urban energy infrastructures.

Keywords: Cross-sectoral Integration, Waste heat utilization, Brewery, Decarbonization, Renewable energy

INTRODUCTION

In 2023 the energy consumption for all the industrial activities in Europe (majorly EU and UK) was about 2750 TWh/year [1-2]. Meanwhile, the total energy consumption for residential sector is 2650 TWh/year [1-2]. The current work focuses on two industrial sectors: 1) Brewery and Whiskey production and 2) Manufacturing industry and their symbiosis with a typical city. Brewery

industry act as source of low-grade heat, which is well suited in meeting the heat demand for manufacturing industry and also, urban district heating networks, where temperature requirements remain typically below 80 °C.

METHODOLOGY

The section first presents, the brewery and manufacturing process description, along with the considered

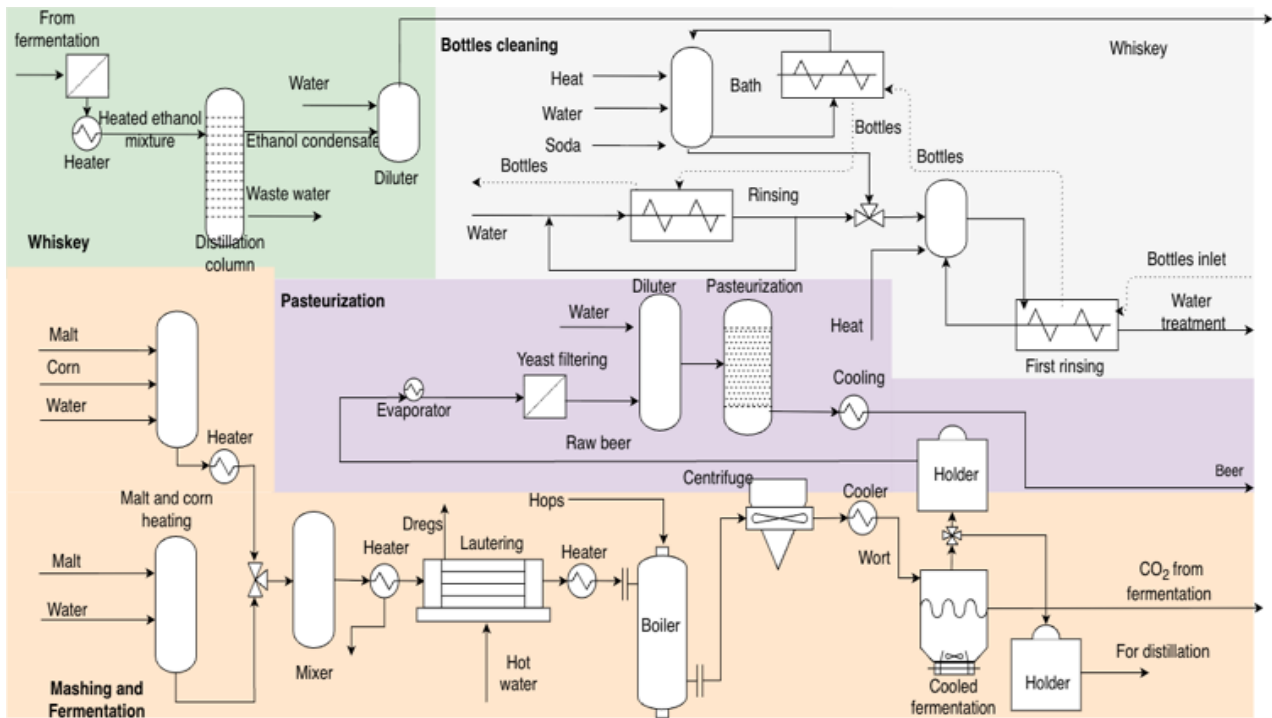


Figure 1. Process flowsheet of the beer and whiskey production with cleaning in place of bottles.

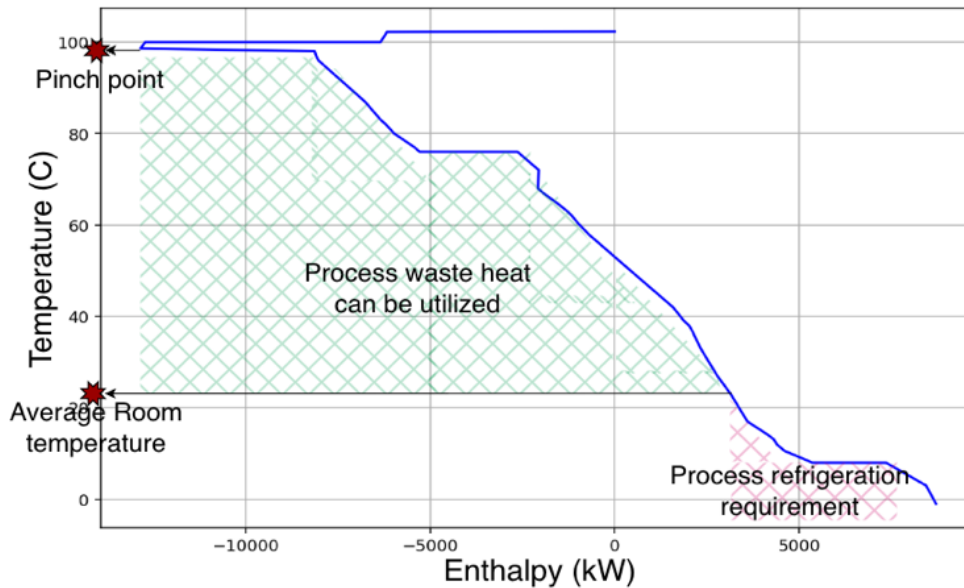


Figure 2. Integrated composite curve of the beer and whiskey production. Green shaded region identifies the process waste heat. Red shaded region identifies refrigeration need.

city demands. Next, the cluster analysis is discussed, followed by explaining in brief the various technological options accounted to meet the industrial utility demands. Finally, discussing about the different approaches for waste heat recovery and its subsequent utilization.

Brewery Industry

The process description is shown in Figure 1.

Primary stages in the production of beer and whiskey include malting and fermentation along with pasteurization for beer [3], [4], and distillation for whiskey [5]. The final products are then bottled. In the current analysis the capacity from beer production is around 49 m³/h, while the capacity of whiskey production is around 2.9 m³/h.

Energy requirement for the processes was

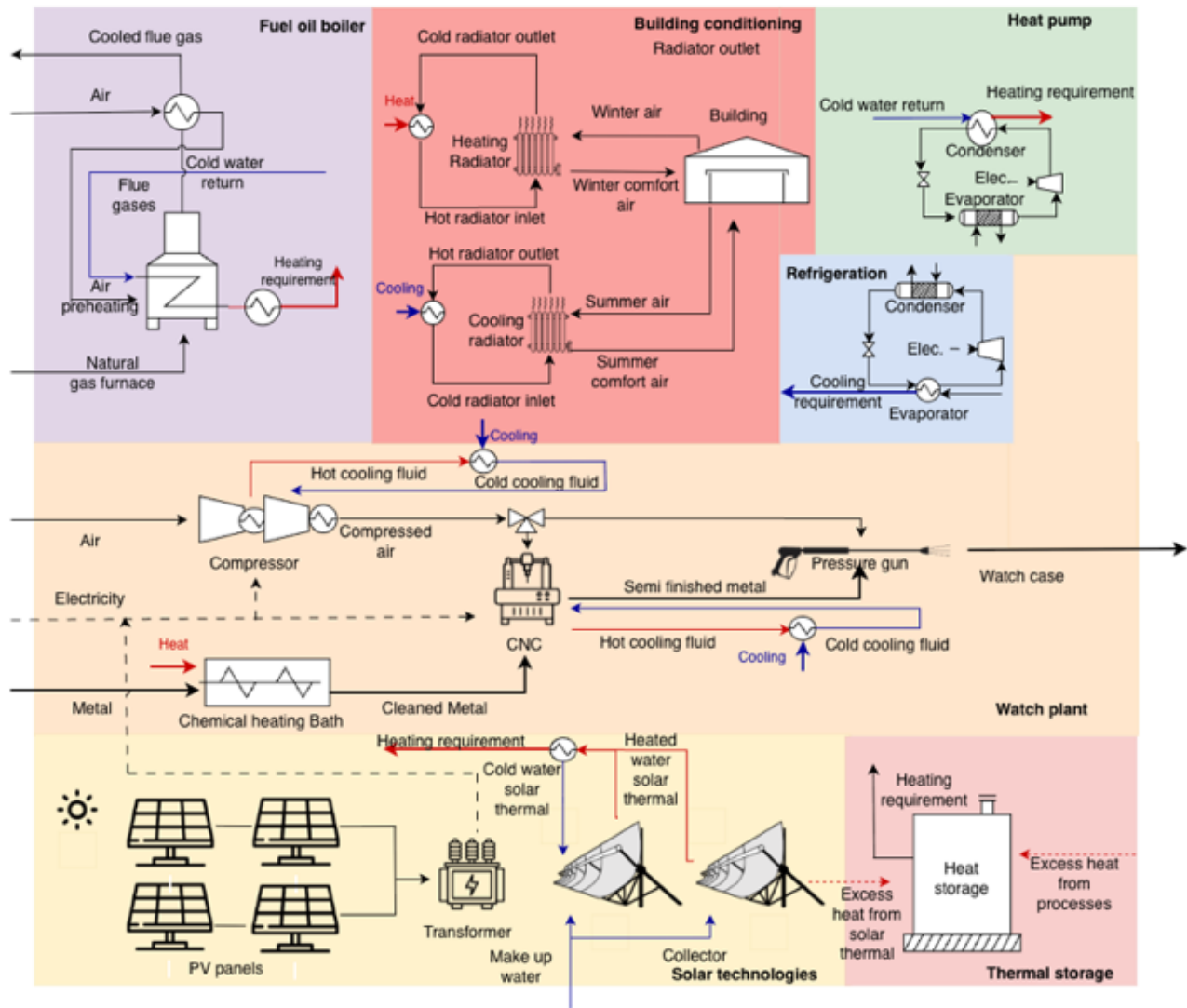


Figure 3. Superstructure of manufacturing industry.

simulated using the opensource modelling tool DWSIM. Process integration was performed using OSMOSE [8]. The waste heat available as well as its amounts are shown in Figure 2. Energy requirement remains constant for the whole year as in this analysis the industry is considered to be a largescale industry.

Manufacturing Industry

The major part of the energy requirement for the manufacturing industry is electricity. Heat is generally required for heating of offices and incoming metal. ([7]). Figure 3 helps in identifying what are the different process involved in machining industry. Energy requirement is varying throughout the year, the variation in energy is depicted in Figure 4.

City

Energy requirement in city generally corresponds to

the energy requirement for residential purpose. The majority of energy consumption is in the form of space heating, water heating, lighting and electrical appliances and cooking.

Energy requirement varies depending upon the season. Variation in energy demand for a city is shown in figure 5.

Cluster analysis

Accurately capturing temporal variations in industrial demand is essential for system-level energy analysis. However, representing demand at an hourly resolution over an entire year (8,760 hours) leads to a substantial computational burden. To address this challenge, a K-means clustering algorithm is employed to aggregate hourly demand profiles into 15 representative operating points distributed across the year. A silhouette score of 0.73 indicates good cluster separation, while the elbow

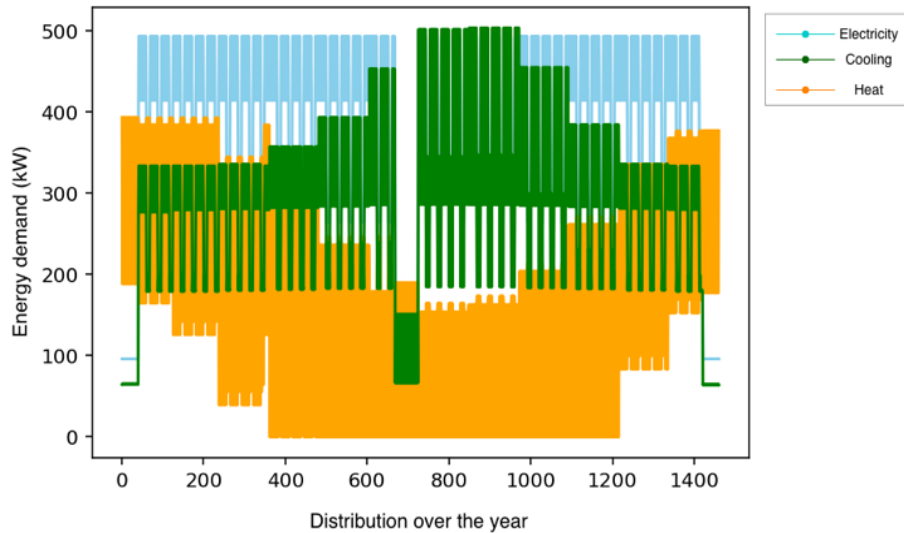


Figure 4. Variation in energy demand across the year in manufacturing unit. Each time step represents a typical 6 hours of working.

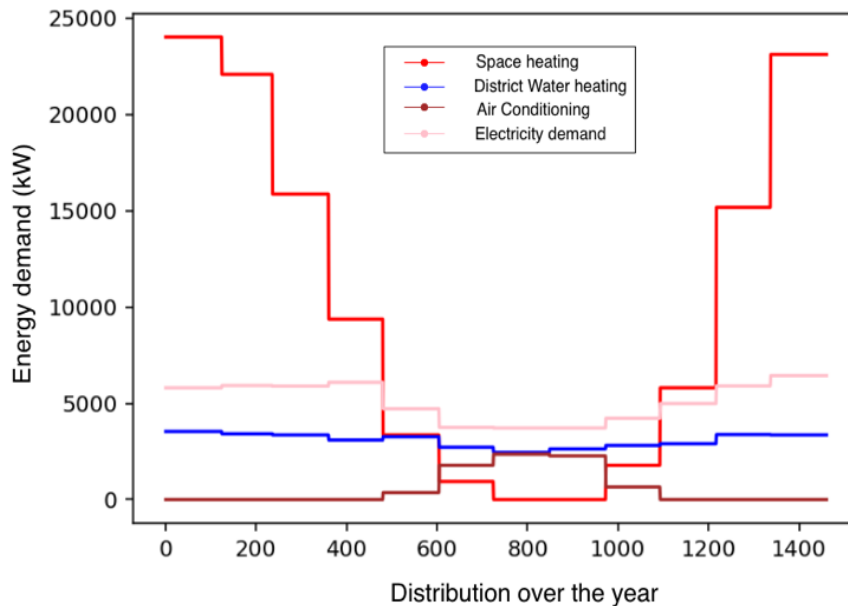


Figure 5. Variation in energy demand across the year in a city. In the figure each time step represents a typical 6 hours of working.

method shows that the within-cluster sum of squares (WCSS) approaches a minimum beyond 15 clusters. The resulting representative points preserve both seasonal and operational variability while significantly reducing computational complexity.

Utilities superstructure

Figure 6 presents the utility supply and waste valorization options available for the brewery industry. A share of the heating and cooling demand can be supplied by heat pumps operating at different temperature levels.

The brewery generates by-products such as dregs and releases waste streams including wastewater and biogenic CO₂. These streams offer multiple valorization pathways. Dregs can be converted into synthetic natural gas (SNG), which can be used either in gas engines for electricity generation or in furnaces for heat production. Wastewater can be treated to produce sludge, which is subsequently converted into SNG via anaerobic digestion. Biogenic CO₂ released during fermentation can be converted into SNG through methanation using hydrogen produced by electrolysis [6].

For the manufacturing (machining) sector, part of

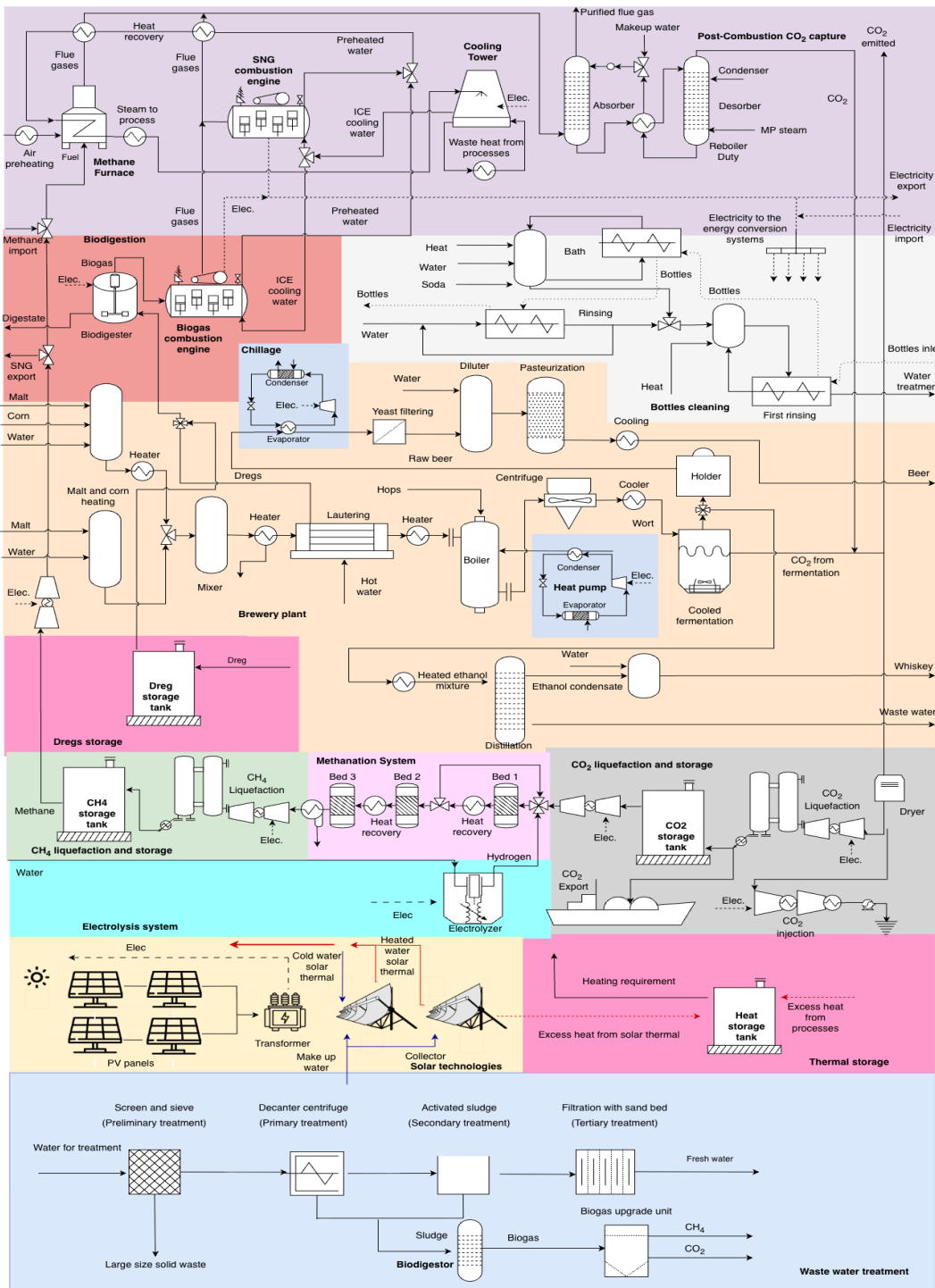


Figure 6: Utilities and waste valorization

the heating and cooling demand can similarly be met using heat pumps, while solar thermal energy is considered as an additional option for supplying low-temperature heat. The corresponding utility options are shown in Figure 3 [7].

For the urban sector, heating is supplied through a

district heating system in which heat is generated centrally and distributed to residential buildings. Centralized heat supply can be provided by either large-scale heat pumps or NG furnaces, while decentralized NG furnaces can alternatively be replaced by decentralized heat pumps [4].

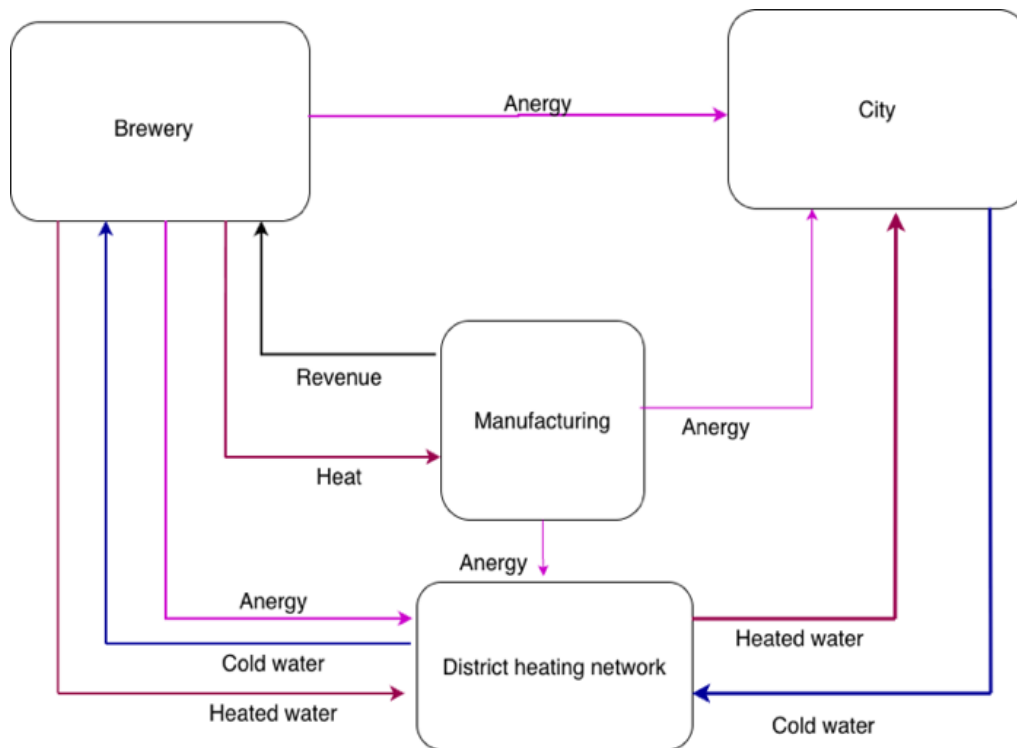


Figure 7. 5th generation heat recovery and utilization

Waste heat recovery.

The brewery industry generates approximately 0.061 kWh of waste heat per liter of beer produced, while whiskey production releases around 2.2 kWh per liter, with most of the waste heat available at temperatures close to 95 °C. For the studied system, this corresponds to a total waste heat potential of approximately 12.76 MW.

Cold outlet from the houses can be heated up to required temperature with the process waste heat released in brewery. In this case some section of district heating network is provided with the help of process waste heat. In brewery and manufacturing industry as depicted in figure. In brewery process as identified from figure 2, there is need of refrigeration system to provide cooling. These refrigeration system act as a source of energy (low grade heat which cannot be directly used in direct heating). The energy act as a source of heat for the evaporator section of decentralized or centralized heat pump and provide heating to the house directly or to the district heating network. All these possible options are depicted in figure 7.

Sensitivity analysis.

Given the multiple utility and waste valorization options shown in Figures 3, 6 and 7, the optimal system configuration is determined using the optimization framework OSMOSE [8]. Technology selection is driven by the

chosen objective function. In this study, total cost (TO-TEX), defined as the sum of annualized investment and operating costs, is used as the optimization criteria.

Key parameters influencing technology selection include electricity price, natural gas price, and carbon tax level. A sensitivity analysis is therefore performed by varying these parameters to evaluate their impact on system configuration, energy self-reliance, and emissions.

RESULT

The analysis is carried out for two distinct system configurations. For the System Configuration 1 (SC 1), all three sectors are fully integrated and allowed to exchange mass and energy flows. In System Configuration 2 (SC 2), brewery, manufacturing sector, and the city operate independently, with no exchange of heat, energy, or mass flows among them.

For both scenarios, a sensitivity analysis is performed and the results are evaluated based on two criteria: (i) improvements in energy efficiency, (ii) reductions in carbon emissions. In all the comparison, results are evaluated against the base system in which the heating requirement is met with the help of natural gas furnace. The cooling requirement is met with the help of cooling tower and refrigeration system. In all the further discussion this scenario will be considered as base system.

Self-reliance of system

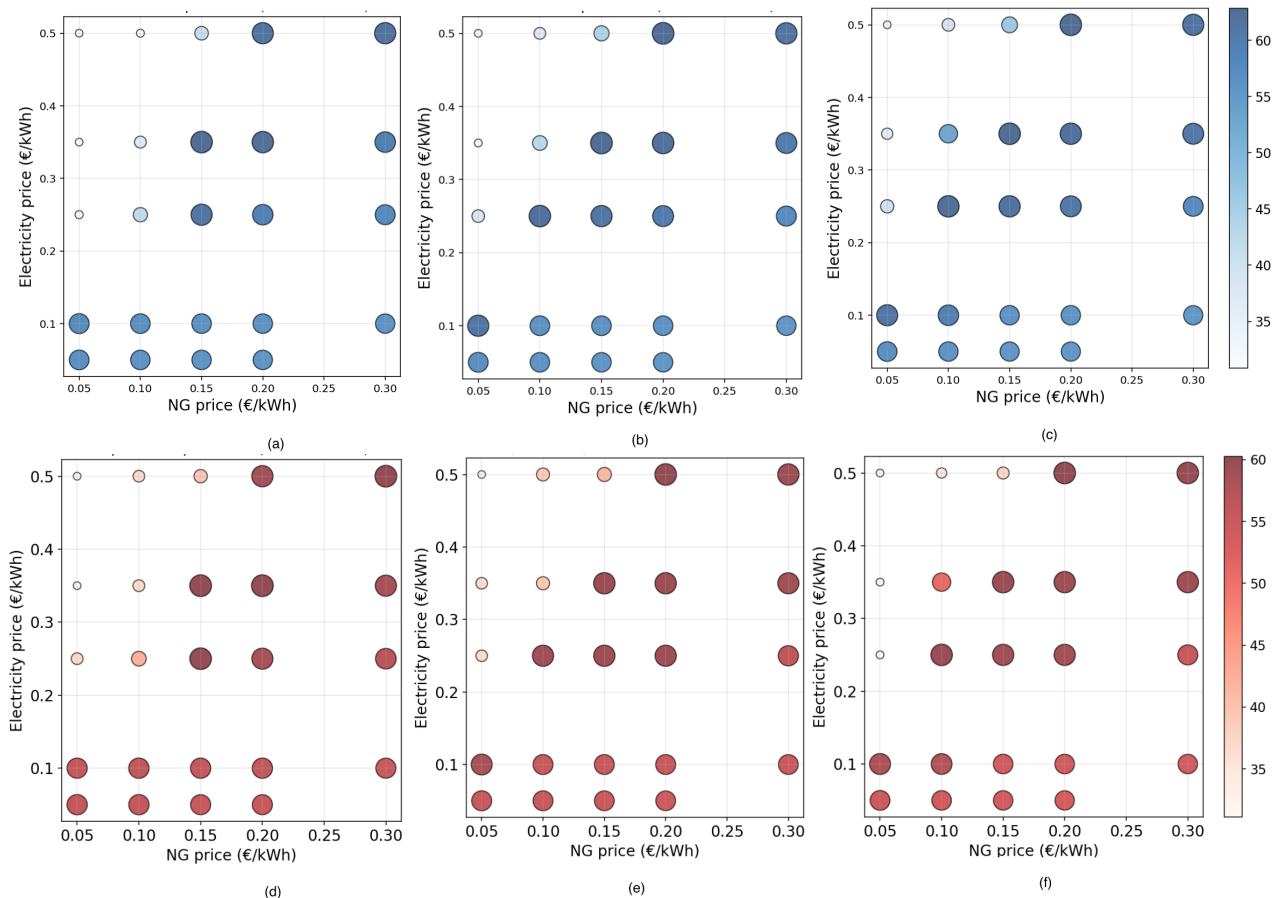


Figure 8: Percentage increase in system self-reliance compared to the base system configuration, across different electricity prices, natural gas prices, and carbon taxes in both system configurations. Panels (a), (b), and (c) correspond to the SC1 while panels (d), (e), and (f) correspond to the SC 2. Graph (a) and (d), corresponds to a carbon tax of 0 €/ton, Graph (b) and (e), value of carbon tax is 80 €/ton; and in Graphs (c) and (f), it is 200 €/ton. Darker and larger points indicate solutions that are more energy independent.

In the base system, total natural gas consumption is approximately 216 TWh/year, while total electricity consumption is around 63 TWh/year. In SC 1 and SC 2, consumption of natural gas and electricity varies as a function of electricity price, natural gas price, and carbon tax. Here, energy self-reliance is defined as the reduction in externally purchased electricity and natural gas relative to the base case. Figure 8 illustrates improvements in energy self-reliance by summing purchased electricity and natural gas in each sensitivity case and comparing them to the base scenario.

Across the sensitivity analysis, energy self-reliance improvement has a very wide range of 61–23% for the SC 1, and also 60–25% for SC 2. The reason for the wide range is due to shift of energy vector. As the price of electricity increases, the optimizer chooses to shift from electrical based utilities to natural gas based utilities. This shift decreases the self sufficiency of the system. The reason is because, heat pumps (electrically driven utility) operate across the system's pinch point and can internally

redistribute energy to meet both heating and cooling demands, thereby reducing external energy purchases.

Comparing (Figure 8 (a) and 8(d)) with (Figures 8 (b) and 8(e)) and, (Figure 8(c) and 8 (f)) respectively, increasing carbon taxes chooses more energy-independent utilities option. The reason is, electrically driven utilities generally exhibit lower carbon emissions than natural gas-based alternatives. As carbon tax increases, the economic penalty associated with CO₂ emissions rises, making low-carbon, electricity-based solutions more attractive despite higher electricity prices. This highlights the role of carbon pricing in incentivizing integrated, low-carbon energy systems, even in contexts with relatively high electricity prices.

Figure 9. compares the energy self-reliance of the SC 1 from SC 2, for the value where carbon tax of zero. Overall, the SC 1 exhibits higher self-sufficiency compared to the SC 2, except in scenarios where electricity prices are high and natural gas prices are low. Under these conditions, the SC 1 consumes more natural gas to

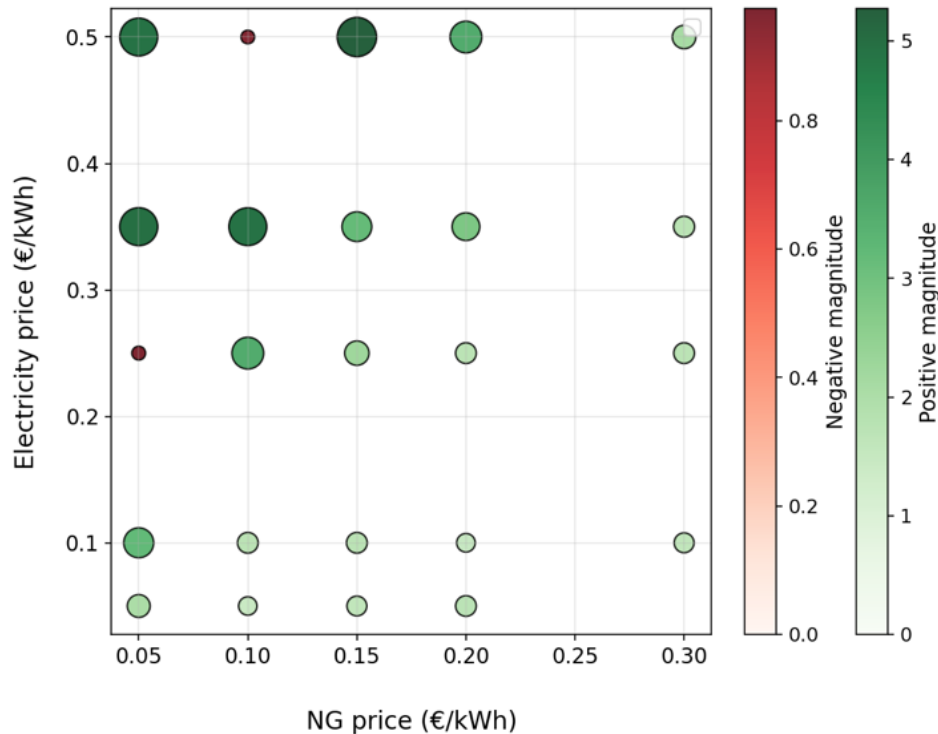


Figure 9. Comparing self sufficiency among different system configurations, across variable electricity and natural gas prices. Green points indicate choices of optimizer where SC 1 results in higher self-sufficiency than the SC 2. Conversely, red point indicate the choices where SC 2 has higher self sufficiency than SC 1. Higher the size and intensity of the color, larger the difference among both the system configurations.

satisfy energy demand, as the absence of a carbon penalty favors cost-optimal but fossil-intensive solution.

Environmental analysis

In the base system configuration, the total amount of CO₂ released into the atmosphere is approximately 14,490 kton/year, of which emissions from fermentation account for around 14,440 kton/year. In the present analysis, only emissions associated with utility choices are considered for comparison. Although fermentation dominates total CO₂ emissions, the analysis focuses on utility-related emissions, as these are directly influenced by system configuration and energy price assumptions.

Figure 10 compares the differences in emission reductions among both the system configuration under varying prices of electricity, natural gas, and carbon tax. When the cost of natural gas is higher than or equal to the cost of electricity, SC 1 exhibits slightly lower emissions than the SC 2. However, the difference is relatively small, ranging between 0.2 and 0.3 kton/year. This can be attributed to energy utilization in the SC 1, which reduces the electricity demand for residential heating. In the same price regime, residential heating in the SC 2 is supplied by decentralized heat pumps operating at

higher temperature levels, resulting in lower coefficients of performance (COP) and higher electricity consumption.

When natural gas is cheaper than electricity, SC 2 shows lower emissions than the SC 1 in some cases. The maximum observed difference is approximately 2.2 kton/year, occurring at a carbon tax of 80 €/ton, an electricity price of 0.35 €/kWh, and a natural gas price of 0.05 €/kWh. Under these conditions, the SC 1 consumes more natural gas due to increased availability of waste heat. For system configuration 1, when a heat pump is selected, it upgrades heat below the pinch point to temperatures above the pinch point for use in brewery processes. This reduces the amount of waste heat available for exchange within the proposed heat-exchange network, thereby increasing reliance on natural gas. This also explains the presence of two red points in Figure 10(a) when the carbon tax is zero, since higher natural gas consumption does not incur any economical penalty for the case.

Scenario analysis

The sensitivity analysis revealed an interesting scenario under specific energy price conditions. When the

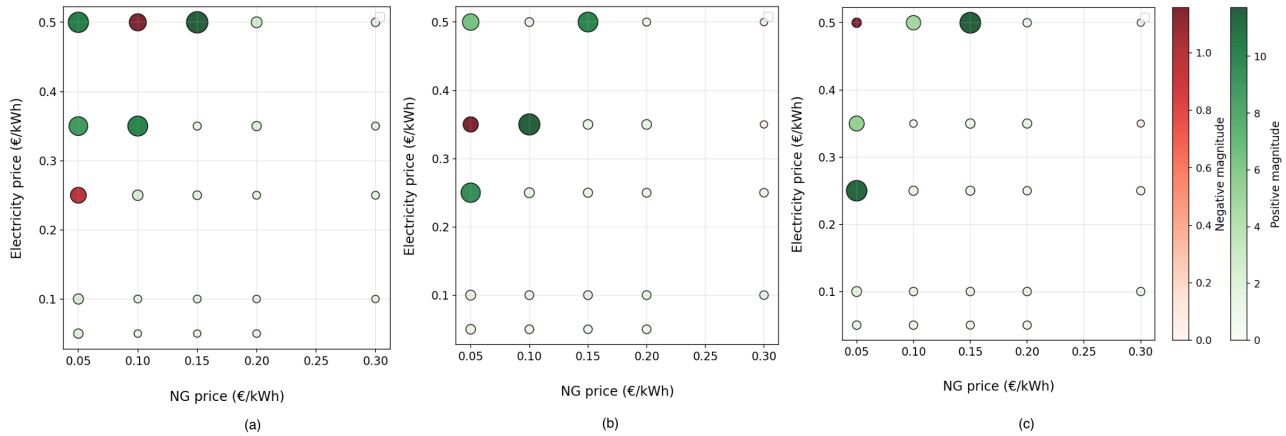


Figure 10: Variation in emission reductions across both the system configuration in variable electricity and natural gas prices. Graphs (a), (b), and (c) represent emission reductions for carbon tax values of 0, 80, and 200 €/tCO₂, respectively. Green points indicate decisions in which SC 1 results in lower emissions than SC 2. Size of green points reflects the absolute difference in emission reduction between the system configurations. Conversely, red points indicate the decision where SC 2 has lower emissions than the SC 1, with larger red points representing greater differences between the two systems.

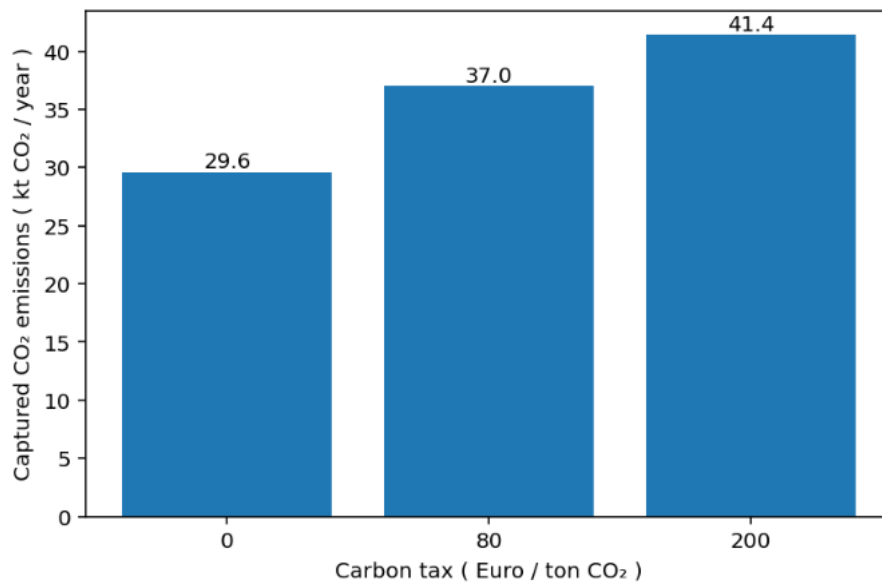


Figure 11. Net amount of CO₂ captured for SC 1 scenario as a function of carbon tax level.

electricity price is approximately 0.05 €/kWh and the natural gas price is around 0.3 €/kWh, the optimizer captures biogenic CO₂ and it is converted into e-methane via methanation.

The capture and utilization of biogenic carbon enables the brewery system to operate in an energetically carbon-negative mode. In the zero carbon tax scenario (0 €/tCO₂), electricity consumption amounts to 691.7 GWh yr⁻¹ for the SC 1 and 1,055 GWh yr⁻¹ for the SC 2, while e-methane production reaches 335 GWh yr⁻¹ and

520 GWh yr⁻¹, respectively. Assuming a grid emission factor of 0.054 kg CO₂ kWh⁻¹, the CO₂ emissions associated with electricity consumption remain lower than the amount of biogenic CO₂ captured from fermentation, resulting in net negative emissions in both cases.

In both the system configurations a consistent trend was observed: increasing carbon tax levels leads to more capture of biogenic CO₂; increasing the net amount of CO₂ captured, thereby enhancing the carbon-negative performance of the system (Figures 11 and 12).

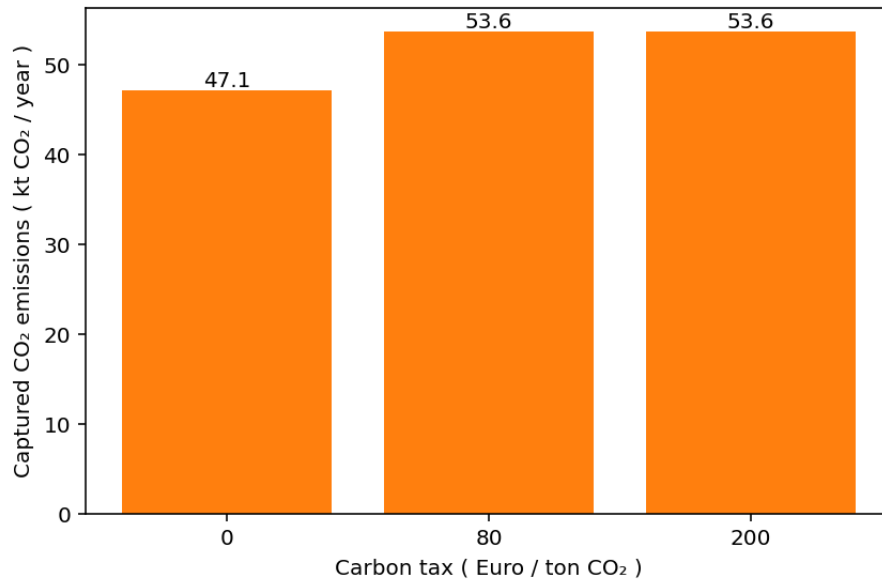


Figure 12. Net amount of CO₂ captured SC 2 as a function of carbon tax level.

Methanation and electrolysis are exothermic, and the resulting heat generation constrains the maximum CO₂ capture through cooling capacity limits. For SC 1, these limits are determined by the combined refrigeration and heat-storage capacities across the brewery, city, and manufacturing sectors enabled by the fifth-generation heat network, whereas in the SC 2 system they are governed by the brewery refrigeration system and cooling tower capacity.

CONCLUSION

This study demonstrates how integrated industrial-urban energy systems can significantly improve energy self-reliance and environmental performance through coordinated utility selection, waste valorization, and heat recovery. By combining temporal demand clustering with cost-optimal optimization using OSMOSE, the analysis highlights the strong influence of energy prices, carbon taxation, and system integration on technology choices.

The results show that SC 1 generally achieve higher self-sufficiency and lower emissions than SC 2 configurations, particularly under higher carbon tax levels. Notably, under favorable energy price conditions, the system enables the capture and conversion of biogenic CO₂ into e-methane, resulting in energetically carbon-negative operation. These findings underline the potential of integrated, low-carbon energy systems and policy instruments such as carbon pricing to support deep industrial decarbonization.

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