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Municipal Solid Waste Valorization into Chemical Solvents for Industrial Symbiosis: Techno-Economic and Environmental Assessment

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ABSTRACT

Waste incineration with combined heat and power (CHP) supplies electricity and heat to cities and industrial clusters but remains a significant source of greenhouse gas emissions. This work develops an optimization-based, system-level decarbonization framework for an integrated waste-to-energy and chemical production cluster under operational, societal, and economic constraints. The framework is applied to a real-world case study including a municipal waste incineration plant, an energy utility system, and multiple chemical production units. A layered decarbonization strategy is implemented. First, energy efficiency is enhanced through waste heat valorization using heat pumps. Second, coordination between industrial actors is improved through solid waste storage management and operational alignment of heat and power supply with demand. Third, alternative feedstocks are introduced to reduce fossil-based inputs. Within the work material and heat-stream inventories are collected, and the required chemical synthesis pathways are modeled using Aspen Plus. The integrated system is optimized within the OSMOSE framework using a multi-period mixed-integer linear programming formulation that minimizes the annualized total cost while accounting for seasonal heat demand and electricity price variability. The results show that waste-heat upgrading alone enables fossil emission reductions of up to 22% while improving overall system profitability. More broadly, up to 80% of fossil-based Scope 1 and Scope 2 CO_2 emissions can be reduced through energy efficiency improvements, system integration, and feedstock substitution prior to carbon capture deployment. To address the remaining hard-to-avoid emissions and enable net-negative operation, post-combustion carbon capture options are evaluated in combination with solid oxide electrolysis cells (SOEC).

Keywords: Industrial symbiosis, Waste valorization, Waste heat, Carbon capture, Process integration

INTRODUCTION

In Switzerland, the most common practice for treating municipal solid waste is incineration. Approximately 30 waste incineration plants are currently in operation, treating about 4 Mt/yr of waste and accounting for roughly 5% of national CO_2 emissions [1]. A large share of these facilities is connected to district heating networks, while a smaller number directly supplies steam to nearby industrial zones. Although this configuration reduces additional fossil fuel combustion for steam generation and residential heating, current systems often fail to fully exploit the efficiency potential of the existing infrastructure. As a result, significant opportunities remain for optimization, particularly through improved valorization of industrial condensate using heat pumps and enhanced coordination between actors to further reduce fossil fuel use. In addition, waste can be used as a feedstock for the production of basic chemicals for nearby industries, extending industrial symbiosis beyond energy exchange to include material flows. This can further reduce the fossil dependency of the chemical sector, which is currently estimated to rely on fossil-based feedstocks for approximately 95% of its raw material input.

This work provides a system-level analysis involving multiple actors, combining process modeling, integration,

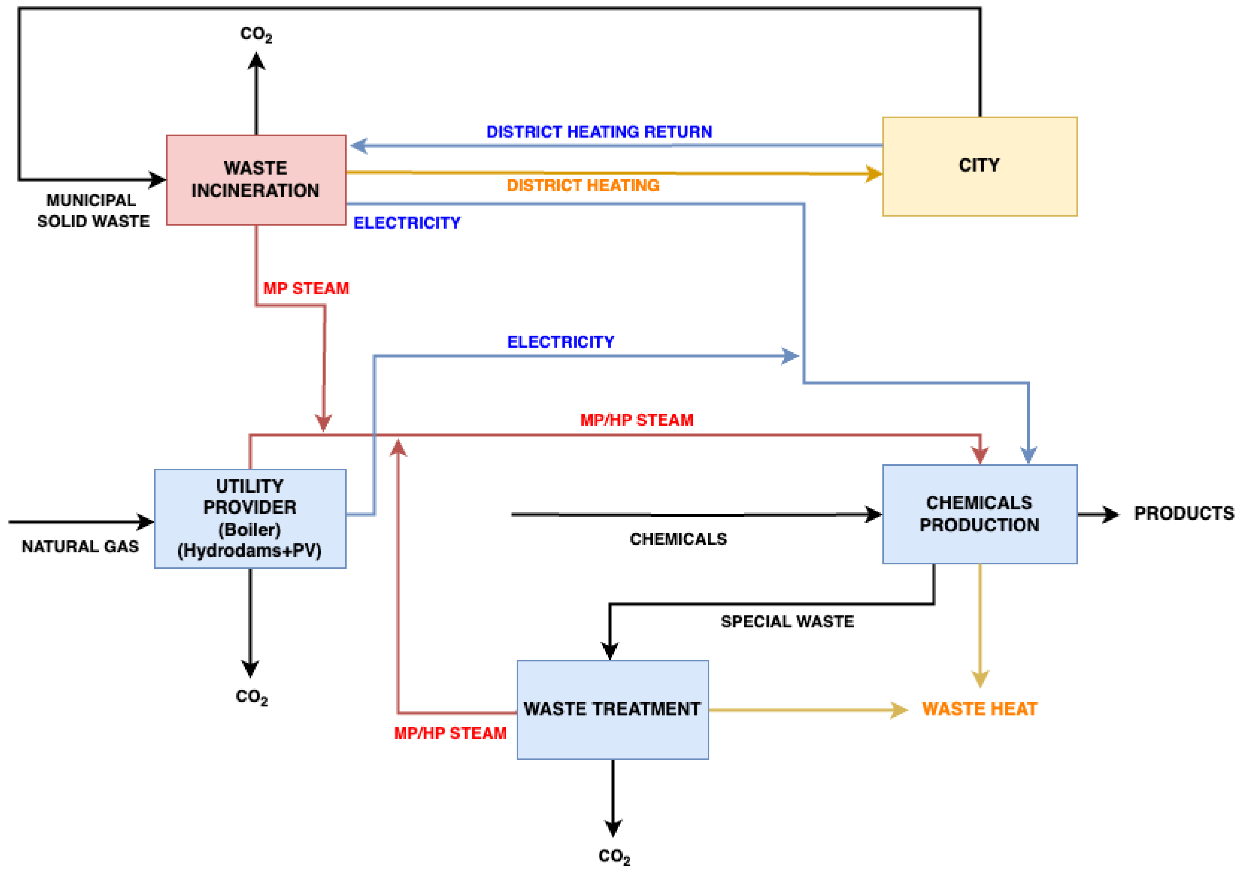

Figure 1. System boundary and energy–material interactions between system actors

and optimization to improve energy efficiency and reduce fossil-based emissions while explicitly accounting for economic constraints. A layered decarbonization approach is adopted, prioritizing measures that are easier to implement and adapt in industrial practice, thereby reducing reliance on and challenges associated with large-scale carbon capture deployment.

METHODS

System Boundary and Actors

Within the defined system boundaries shown in Figure 1, several industrial actors are considered. The first is the waste-to-energy (WtE) plant, which treats municipal solid waste (MSW) and supplies energy in the form of medium-pressure (MP) steam and electricity to the chemical processes, as well as hot water to the district heating network. The second actor is the utility company, which provides heat, power, and special waste treatment services to the chemical processes. Its available assets within the system include a natural gas boiler for the production of MP and high-pressure (HP) steam, waste incineration units capable of supplying MP and HP steam, and renewable power generation units, including hydropower dams and photovoltaic (PV) fields. The third actor consists of the chemical production units, which require electricity, steam, and basic chemical feedstocks, and produce high-value chemicals for the market. These units also benefit from cooling services provided by the utility company, generating low-grade waste heat that can be upgraded and valorized within the system. The final actor is the city, which requires heat for most of the year due to local climatic conditions, supplies municipal solid waste to the WtE plant, and acts as a net importer of electricity, with limited photovoltaic installations and hydropower capacity.

Although a certain degree of industrial symbiosis already exists between these actors, their current level of coordination remains far from optimal. As a result, significant opportunities for improving energy efficiency and reducing fossil-based carbon emissions remain unexploited. This work addresses these gaps by strengthening existing energy distribution and material exchange links and introducing new integration pathways within the system. The coordination of actors is optimized using a system-level approach to achieve the decarbonization objectives outlined above.

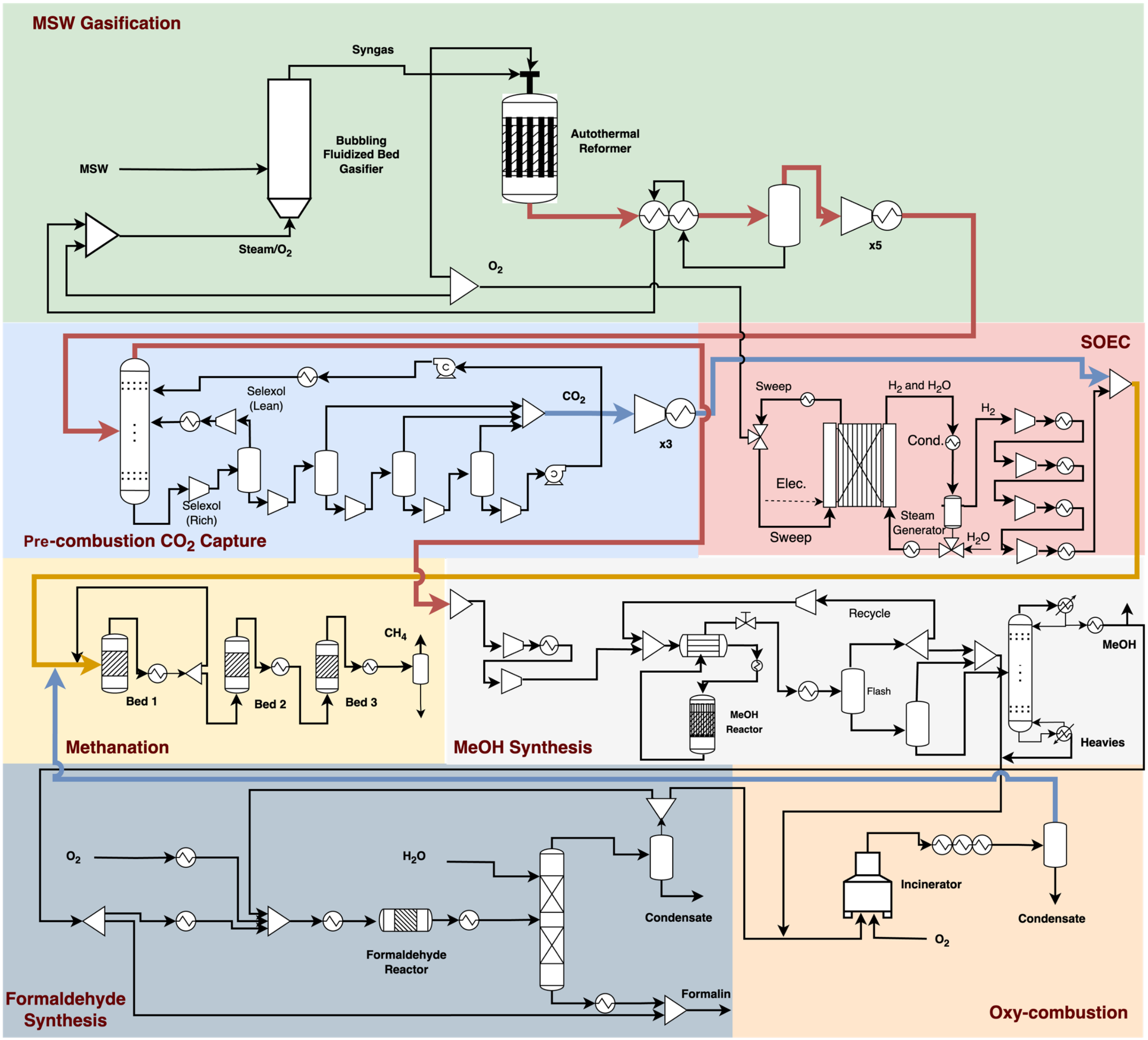

Figure 2. Superstructure of chemical synthesis pathways considered in the study, including municipal solid waste gasification for syngas production, pre-combustion carbon dioxide capture, H_2 production with SOEC, oxy-combustion for CO_2 capture, and downstream synthesis of methanol, formaldehyde, and synthetic natural gas.

Energy Demand and Supply in the System

In the current reference state of the system, approximately 67% of the total heat demand for the chemical processes is supplied as MP steam, while the remaining demand is covered by HP steam. Around half of the MP steam demand is met by the WtE facility, with the remainder supplied by the NG boiler operated by the utility company. For HP steam, the dominant share is provided by the incineration of special waste, accounting for approximately 80% of the supply, while the remaining share is supplied by the NG boiler. All heat demand of the city is covered by the WtE facility and represents approximately one fifth of the heat demand of the chemical processes.

In terms of power distribution, approximately 40% of the electricity consumed by the utility company and the chemical processes is supplied by the WtE facility. Around 8% is generated by PV installations, while the remaining share is provided by hydropower dams, with the possibility of electricity injection into the grid in the case of excess generation.

As a consequence of the current heat and power generation and distribution, approximately 65% of the total CO_2 emissions originate from the WtE facility, of which about half corresponds to biogenic carbon. Around 25% of the CO_2 emissions are associated with the incineration of special waste, while the remaining 10% result from the combustion of natural gas for steam supply.

Process Modeling of Chemical Pathways

MSW can be valorized beyond direct incineration by converting it into syngas for the production of basic chemicals and by recovering high-grade heat for industrial applications. In this context, this study considers a superstructure of chemical synthesis pathways that enables the integrated valorization of material and energy streams within the overall system, as shown in Figure 2.

For the gasification of MSW, a model of bubbling fluidized gasifier using oxy-steam as the gasification agent, operated at 750 °C and 1 bar was used based on the study of Sebastiani et al. [2]. The chemical properties of the waste used is given in Table 1.

Table 1. Proximate and ultimate analysis of MSW (fuel as received)[2]

Composition		MSW
Proximate Analysis [%]	M	14.6
	FC	8.90
	VM	64.7
	Ash	11.8
Ultimate Analysis [%]	C	41.8
	H	5.05
	N	3.02
	O	23.4
Net calorific value [MJ/kg]		19.9

The produced syngas passes through an adiabatic autothermal reformer and is subsequently cooled to condense water. The resulting syngas is processed in an selexol-based carbon capture unit operating at 30 bar with 90% capture efficiency, adjusting the composition to the stoichiometric number (SN) of slightly above 2.0 required for methanol synthesis [3]. The resulting syngas after the upgrading has a molar composition of 68.3% H_2, 31.3% CO, 0.4% CO_2.

$$SN = (x_{H_2} - x_{CO_2})/(x_{CO} + x_{CO_2})$$

The methanol synthesis process is operated isothermally at 210 °C and 90 bar, based on Lurgi's Mega-Methanol® technology, achieving a mass yield of 95.8% [4]. The produced methanol can either be used as a base chemical within the system or converted to formaldehyde via the Formox® process, which is based on the catalytic oxidation of methanol [5]. The reaction is operated at 250 °C and 1 bar. Following formaldehyde production, the product is mixed with methanol and water to obtain a formalin solution with a composition of 38% formaldehyde, 14% methanol, and 48% water on a molar basis.

The CO_2 captured during syngas upgrading and from the oxy-combustion of purge streams is utilized in a methanation process coupled with SOEC, following the approach proposed by Flórez-Orrego et al [6].

Definition of Decarbonization Options

Following the layered decarbonization strategy, five system configurations are defined and analyzed. Each configuration progressively extends the level of integration, flexibility, and decarbonization options considered in the optimization framework.

- **Base**: The base configuration represents the reference system as defined in the previous sections, without additional flexibility or decarbonization measures.
- **A**: In this configuration, waste heat available from chemical synthesis processes and special waste incineration is valorized through the integration of decentralized and centralized steam-generating heat pumps. WtE is operated considering historical trends.
- **B**: Building on Configuration A, the waste-to-energy (WtE) facility is allowed for operational flexibility through the management of seasonal solid waste storage. The facility can adjust the allocation between steam, electricity, and district heating production in response to the demands of other system actors
- **C:** In addition to the features of Configuration B, waste heat from chemical synthesis and special waste treatment is further upgraded via heat pumps and allowed to supply the district heating network, thereby introducing competition with district heating generated by the WtE facility.
- **D**: The final configuration extends Configuration C by integrating a municipal solid waste (MSW) gasifier. The produced syngas is used as a feedstock for the synthesis of basic chemicals (i.e., methanol and formalin) at the chemical site. In addition, pre-combustion CO_2 captured from the gasification process is combined with hydrogen produced by a solid oxide electrolysis cell (SOEC) to increase chemical yields or enable the production of synthetic natural gas.

Each configuration is also evaluated with the integration of post-combustion carbon capture based on MEA for the capture of all the remaining CO_2 emissions within the system boundaries. Configurations including carbon capture are denoted by a prime symbol (') throughout this study.

Optimization Framework and Problem Formulation

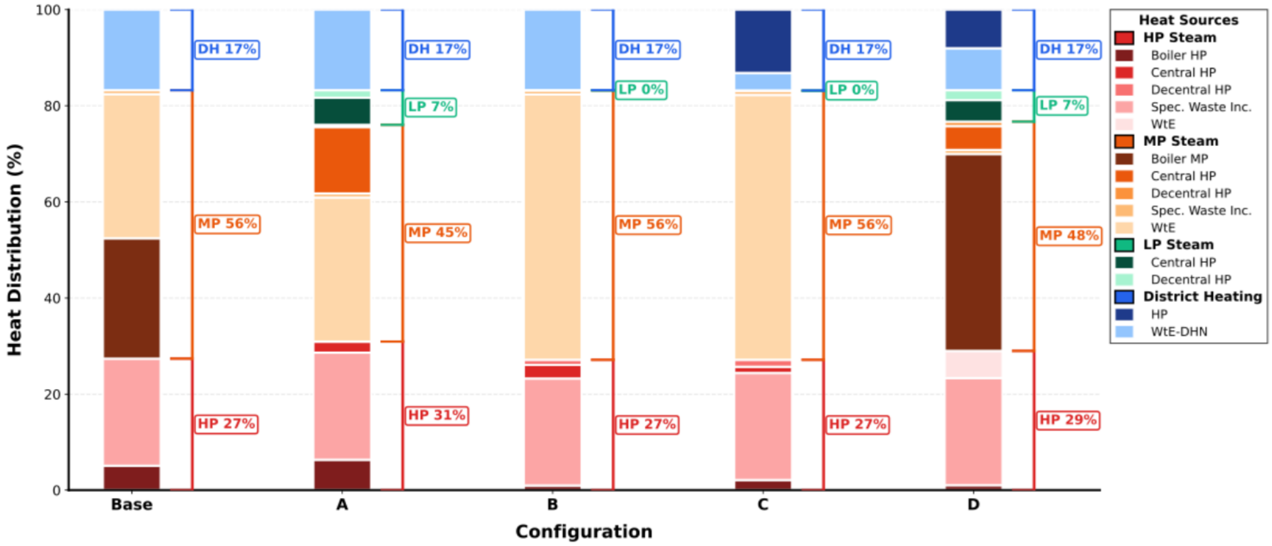

Figure 3a. Heat distribution by steam pressure level and heat source across the different decarbonization configurations.

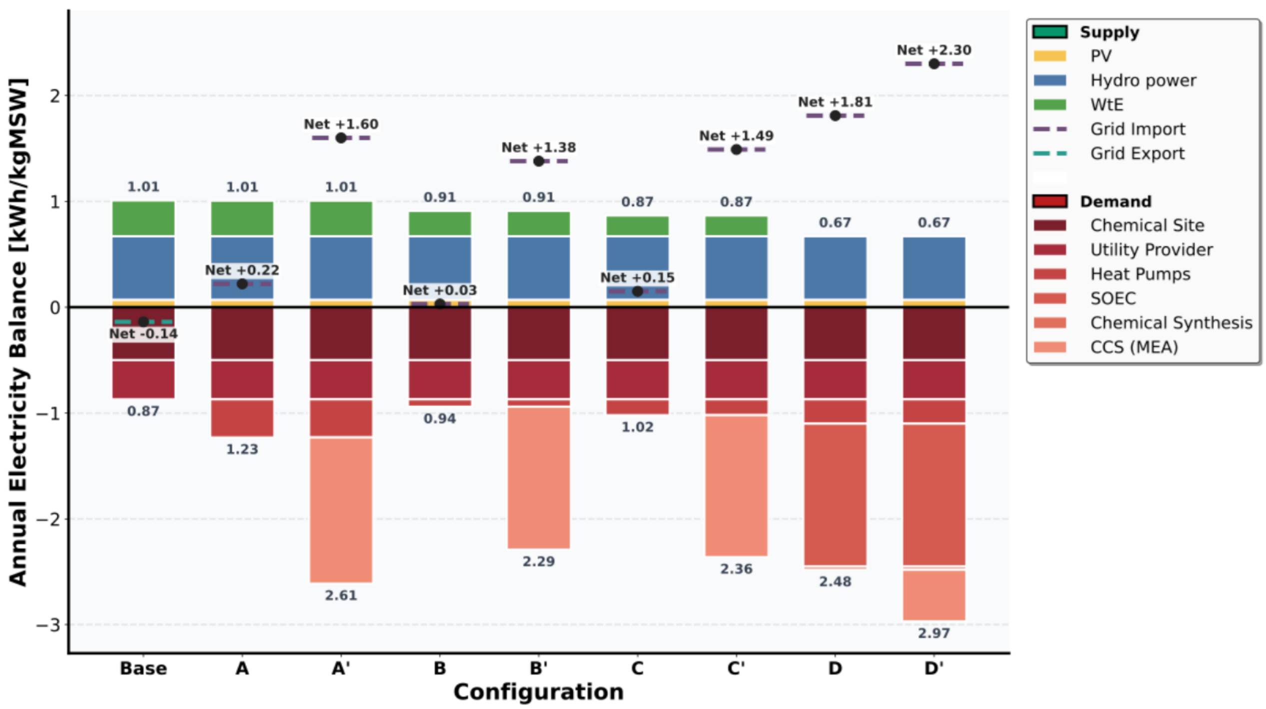

Figure 3b. Annual electricity balance of the integrated system across the different decarbonization configurations, showing electricity supply and demand contributions.

The proposed configurations are integrated and optimized within the OSMOSE Lua platform to identify cost-optimal operating conditions for the superstructure, as defined by the objective function presented below [7].

$$\min Cost_{tot} = \sum_{u \epsilon Units} \left[\sum_{t \epsilon Time} [(Cop1_u \cdot Y_{u,t} + Cop2_u \cdot M_{u,t})\Delta t + Cinv1_u \cdot Y_u + Cinv2_u \cdot M_u] \right]$$

- $Cop1_u$ [EUR/h]: fixed operating cost of unit u,
- $Cop2_u$ [EUR/kWh or EUR/kg]: variable operating cost of unit u,
- $Y_{u,t}$ [-]: integer variable standing for the activation of the unit u at a time t,
- $M_{u,t}$ [kg/h or kW]: continuous variable standing for the load of the unit u at a time t,

- $Cinv1_u$ [EUR/y]: fixed annualized cost of unit u,
- $Cinv2_u$ [EUR/kWh or EUR/kg]: variable annualized cost of unit u,
- Y_u [-]: integer variable for the activation of the unit u, maximum value of $Y_{u,t}$,
- M_u [kg/y or kWh/y]: maximum load of the unit.

The problem is solved using a multi-period formulation with 10 representative clusters, capturing steam demand of chemical processes, district heating requirements, MSW supply to WtE, and electricity/natural gas prices based on the Swiss spot market [8]. The electricity supply is considered to be fully decarbonized based on the real-case arrangements defined within the system boundaries. A Scope 2 emission factor of 0.05 $kgCO_2$/kWh is applied to the natural gas supply.

RESULTS AND DISCUSSION

This section presents and discusses the results of the OSMOSE optimization framework for the different configurations, focusing on energy distribution, fossil CO_2 emissions, and the resulting economic trade-offs.

Energy Distribution and Electricity Demand

The heat distribution within the system for each configuration is shown in Figure 3a. In Configuration A, where only heat pump integration is introduced at temperature levels of 40 °C and 70 °C, the boiler supplying MP steam is no longer required. In contrast, the HP boiler remains in operation due to the higher temperature lift required. As a result, approximately 90% of the available waste heat is upgraded to LP and MP steam levels, while only about 10% is upgraded to HP steam, primarily during periods of low electricity spot prices.

In Configuration C, when the WtE facility is allowed to better align its operation with the other system actors and waste heat can be supplied to the district heating network, it becomes the sole provider of MP steam. At the same time, its direct contribution to district heating is reduced by approximately 80%. Given the high coefficient of performance of the heat pumps supplying the district heating network (COP = 4.3), the system favors cascading heat through the chemical processes while using the available waste heat primarily for meeting the city's heating demand. As a result, only about 18% of the available waste heat is utilized for steam generation.

Finally, in Configuration D, the system enables the production of synthetic natural gas, and the heat released from syngas cooling, exothermic methanol and formaldehyde synthesis, and purge stream combustion is recovered and reused for steam generation for the gasifier and the SOEC. As a consequence, the contribution of waste treatment to steam supply is reduced and the MP boiler is reactivated. In this configuration, approximately 60% of the upgraded waste heat is allocated to steam generation, while only about half of the city's heating demand is supplied via heat pumps.

As shown in Figure 3b, at its current electricity generation capacity the system is not able to remain fully self-sufficient and therefore requires electricity imports across all configurations. In Configuration A, the installation of heat pumps leads to an increase in electricity consumption of 0.36 kWh_{EE}/kgMSW. However, when improved alignment between system actors is introduced in Configuration B, the system reaches near self-sufficiency, with electricity imports limited to only 0.03 kWh_{EE}/kgMSW. The highest electricity consumption and imports are observed in Configuration D, as the SOEC installation requires 1.35 kWh_{EE}/kgMSW and electricity generation from the WtE turbine is no longer available. As the heat demand of the MEA carbon capture unit is electrified, electricity consumption increases by up to 1.38 kWh_{EE}/kgMSW in Configuration B′. In contrast, this increase is limited to 0.49 kWh_{EE}/kgMSW in Configuration D′, since a larger fraction of the carbon contained in the MSW is retained within chemical products, thereby reducing the required size of the MEA carbon capture unit

CO_2 Emissions Performance

With the integration of heat pumps leading to the significant reduction in boiler usage, as illustrated in Figure 3a, net fossil emissions decrease by 17% in Configuration A, as shown in Figure 4a. Improved alignment between system actors and cascading of heat through the chemical processes before heating the city further extend the reduction in fossil emissions to 22% compared to the base case.

The remaining fossil CO_2 emissions consist of approximately 60% originating from MSW incineration and 40% from the incineration of special waste generated by the chemical processes; however, the system remains far from achieving carbon neutrality. In Configuration D, the valorization of waste as a feedstock for basic chemical production reduces net emissions to 0.23 $kgCO_2$/kgMSW. However, due to the combustion of synthetic natural gas, fossil CO_2 originating from the MSW is released again into the environment. Therefore, the integration of post-combustion carbon capture is required to achieve net negative emissions. With the deployment of MEA-based carbon capture and assuming that all remaining residual CO_2 is captured and permanently stored, the system can reach net negative emissions of −0.5 $kgCO_2$/kgMSW.

Economic Performance and Cost Trade-offs

The breakdown of marginal operating and capital expenditures for all configurations is shown in Figure 4b. Across Configurations A–C, optimization of the existing

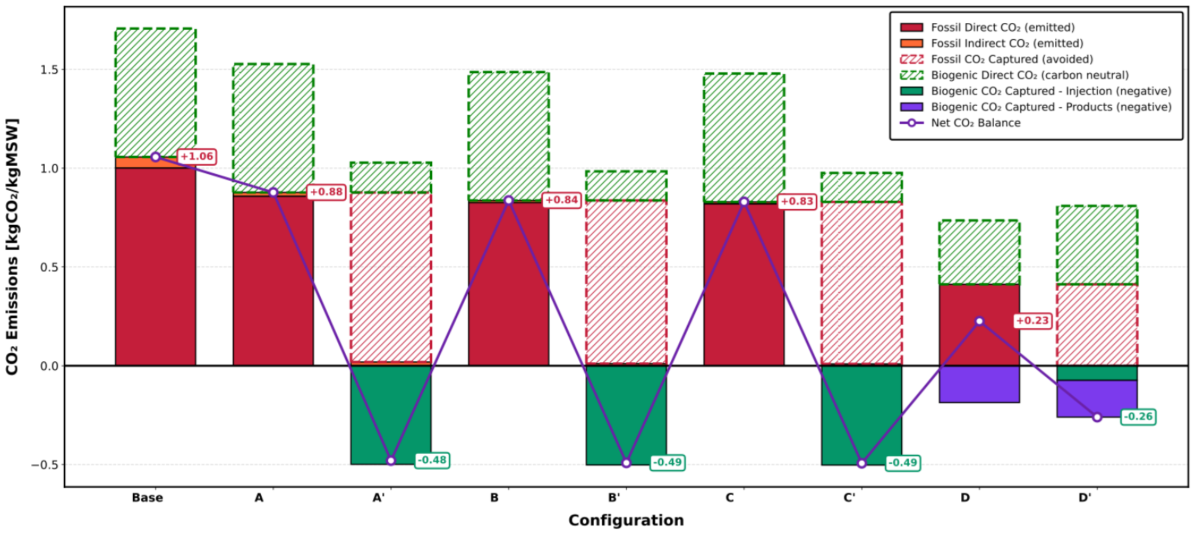

Figure 4.a. Breakdown of fossil and biogenic CO_2 emissions, captured CO_2, and net CO_2 balance across the different decarbonization configurations, normalized per kg MSW.

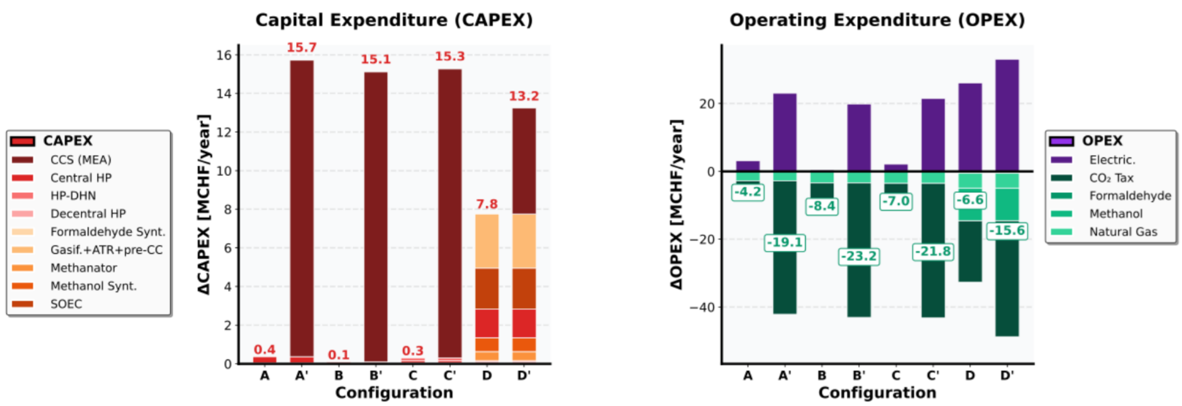

Figure 4.b. Breakdown of annualized capital expenditure (CAPEX) and operating expenditure (OPEX) across the different decarbonization configurations.

infrastructure combined with the installation of heat pump solutions requires limited capital investment and yields annual savings of up to 8.3 MCHF/year, with the maximum savings observed in Configuration B. In contrast, Configuration D results in a net loss of 2.2 MCHF/year. Although savings from avoided CO_2 taxes and additional revenues from methanol and synthetic natural gas exports exceed the required capital investments, the high cost of electricity imports ultimately leads to an overall net loss.

The integration of CCS technologies results in only a limited reduction in profitability for Configuration A'-C', amounting to approximately 0.2 MCHF/year, considering an average annual electricity spot price of 0.08 CHF/kWh and a conservative carbon price of 85 CHF/tCO_2 captured.

CONCLUSIONS

This work has demonstrated a systemic analysis of a real-world case study involving multiple actors within a symbiotic relationship, including a waste incineration facility, a utility company, a cluster of chemical industries, and the city. The analysis aimed to reduce fossil CO_2 emissions while concerning economic profitability through the combined use of process modeling, integration, and optimization methodologies.

The results showed that as a short-term solution, integration of heat pump technologies, optimizing the steam supply levels through means of heat cascading can lead to moderate reductions in fossil CO_2 emissions while providing significant economic benefits. However, these measures are followed by increase in electricity consumption, highlighting the need for adequate preparation of national electricity infrastructures in case of mass adaptation.

While cost-effective and easily adoptable technologies are desirable, they fail on their own to achieve net-zero/negative operation. The findings of this work show the benefit of a layered decarbonization approach for a decarbonization pathway, in which energy efficiency and heat integration measures are prioritized before introducing capital intensive solutions. In the longer term, full defossilization requires a transition toward alternative renewable feedstocks and explicit consideration of carbon circularity to avoid burden shifting across sectors.

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