SUPERSTRUCTURE-BASED APPROACH TO ASSESS THE HEAT PUMPING AND RENEWABLE ENERGY INTEGRATION POTENTIAL IN THE SUGAR INDUSTRY

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ABSTRACT

The study examines the feasibility of integrating heat pumps (HPs) and renewable energy in the sugar industry to advance decarbonization. It explores different routes for energy supply, contrasting them with a natural gas (NG)-fired base-case route. The alternatives include bio-digestion of beet and pulp waste to produce biomethane (bio-CH_4) used in the process, hydrogen boiler, and electric boiler (full electrification using renewable electricity). Each route also incorporates HPs, utilizing waste heat primarily from evaporation and drying processes. Additionally, CO_2 capture (CC) units can be optionally installed. Evaluation of the superstructure employs a systemic methodology with total specific cost (€/t_{sugar}) and total specific emissions (t_{CO2}/t_{sugar}) as objective functions for each route. Detailed blueprint (BP) models of sugar production for each route cover mass and energy balances, CAPEX and OPEX, and material and energy resource costs. Optimization is conducted using the OSMOSE Lua framework with a mixed integer linear programming (MILP) approach. Three energy scenarios (2023, 2030, and 2050) are established, influencing prices of NG, hydrogen, electricity, and CO_2 emissions. In the 2023 scenario, integrating bio-CH_4 with HP emerges as the most cost-effective option, reducing costs by 15% compared to the base-case. However, the optimal solution adds CC and HP to the bio-CH_4 route, reducing costs by 9% while achieving a 133% emissions reduction, resulting in net negative emissions. By 2030, routes with HP become more favorable with slightly lower electricity and hydrogen prices. bio-CH_4 with HP and CC remains the best choice, cutting costs by 60% and maintaining 133% emissions reduction. In the 2050 scenario, decreased electricity and hydrogen prices, coupled with a higher CO_2 emission price, make the base-case the most expensive. Nonetheless, bio-CH_4 routes remain viable, with hydrogen and electric boiler-based routes also feasible due to cheaper energy prices.

1 INTRODUCTION

The European Union (EU) stands as a global leader in combating climate change through its ambitious policies and proactive measures. Committed to the targets set forth in international agreements, the EU has pledged to slash its emissions by at least 55% by 2030 compared to 1990 levels. However, achieving these targets necessitates comprehensive emission reduction strategies across all sectors. Among these, the food and beverages sector stands out as one of Europe's most energy-intensive industries. For instance, it ranks as Germany's sixth most energy-intensive sector (Fleiter et al., 2013), contributing 5.6% to the nation's total final energy consumption. In this sector, the predominant energy sources comprise over 60% natural gas (NG), followed by 29% electricity and 5% district heat (Destatis, 2021). Sugar is a crucial product of food and beverages sector, with an annual production of 170 million tonnes from sugarcane and sugar beet across more than 130 countries. The process is highly energy-intensive, requiring heat to evaporate water at temperatures ranging from 15 to 150 °C. The total CO_2 emissions of the sugar sector in EU is 6.41 million tonnes of CO_2 per year (65.10 t_{CO2}/t_{beets}). According to the European Association of Sugar Manufacturers (CEFS), the EU sugar industry has made significant strides in emission reduction, with emissions decreasing by 59% between 1990 and 2021 (CEFS, 2023).

However, given the prevailing energy crisis, it has become economically imperative to reduce energy consumption and to transition away from fossil fuels.

Various options for decarbonizing the sugar sector have been proposed and studied, including the utilization of heat pumps (HPs) to enhance energy efficiency and switching to renewable sources like hydrogen, converting bio-waste into biofuels, and fully electrifying energy sources. The Lawrence Berkeley National Laboratory, in collaboration with Global Efficiency Intelligence, published a report on the application of industrial HPs in the U.S. manufacturing industry. According to this report, the total energy demand of the U.S. sugar beet industry is approximately 100 PJ/year. Implementation of high-temperature heat pumps (HTHPs) could reduce this demand by 5 PJ/year, while addition of steam-generating heat pumps (SGHPs) could save around 51 PJ/year by 2050. These measures could result in annual fuel savings of 7 PJ and 84 PJ, as well as a reduction in CO_2 emissions of 0.4 million tons and 4.6 million tons respectively, by 2050 (Zuberi et al., 2022). Similarly, Dumont et al. (2023) employed the bottom-up approach to study the integration of HTHPs in the German food and beverages industry from a techno-economic point of view. As per their findings, the innovative HTHP technologies have the capacity to fulfill 12 TWh of process heat demand within the German food and beverages industry, simultaneously reducing emissions by 9% based on Germany's existing electricity fuel mix. With a conservative carbon tax of €38 per ton of CO_2 equivalent or higher, HTHPs become cost-competitive in comparison to an optimized fossil fuel-based alternative.

Brooks et al. (2008) conducted a study to address the energy supply challenges in the sugar industry by exploring alternative treatments for sugar beet pulp (SBP) through anaerobic digestion for biogas production. Lab-scale experiments validated SBP as a suitable substrate for anaerobic bacteria. Pilot-scale experiments optimized processes for efficient biogas production, with both single-stage and two-stage configurations showing similar removal efficiency. Large-scale implementation at a Hungarian sugar factory demonstrated significant potential, with the biogas produced from digesting SBP substituting approximately 40% of the required NG for thermal energy during sugar processing. Similarly, Suhartini et al. (2018) studied the biogas/methane potential of SBP and its performance in semi-continuous digestion, as well as to analyze the nutrient and potentially toxic element (PTE) content of the resulting digestate for agricultural utilization. Through Biochemical Methane Potential (BMP) testing and semi-continuous anaerobic digestion trials, SBP exhibited significant promise as a feedstock, with an average BMP of 0.321 L CH_4/g of volatile solids and a biogas potential of 0.605 L/g volatile solids. Semi-continuous operation further confirmed SBP's favorable characteristics for anaerobic digestion. Furthermore, according to CEFS (2023), utilizing SBP to generate heat and power, either directly or via biogas, is on the rise, especially in areas lacking a local animal feed market for the SBP. In such cases, dehydrating the SBP for transportation and other uses becomes necessary to market it as animal feed. Therefore, utilizing SBP for biogas/biomethane (bio-CH_4) can help in reducing the energy requirements of sugar industry and will facilitate the transition to greener energy for decarbonization (Gartland & Ribera, 2022). Estimates from major sugar producers suggest that a significant portion of SBP, ranging from 55% to 60%, could effectively fulfill their energy needs, leaving ample supply for other applications (Nordzucker, 2023).

Regarding fuel-switching options, hydrogen emerges as a potential alternative for the sugar industry, although research on its utilization within this sector remains limited. Hydrogen, as a renewable or low-carbon alternative to NG for heat generation in sugar factories, requires modifications to existing burners for compatibility. Co-firing hydrogen with NG or using it in oxyfuel burners can enhance combustion efficiency and virtually eliminate NOx emissions (Hart et al., 2015). However, limitations persist due to the high cost and low availability of low-carbon and renewable hydrogen, with current production primarily reliant on NG. Challenges also arise in distribution, as the high energy demands of sugar production necessitate pipelines for transport, requiring significant investment. On the other hand, electric boilers, including electrode boilers, are also proposed as an alternative for complete electrification of sugar production process. These boilers offer higher thermal capacities and can produce steam at high temperatures and pressure, with nearly 99% efficiency. They require minimal process reconfiguration during installation, resulting in lower capital expenditure compared to other options like HTHPs (Berenschot et al., 2017). However, the economic viability depends on grid reliability and electricity prices, with potential attractiveness at €50/MWh (Geres et al., 2020). Yet, future electricity price projections vary, raising questions about long-term feasibility (RTE, 2022).

The discussion presented above highlights the promising pathways for decarbonizing the sugar industry. However, their success depends on various future factors including the availability and technology readiness level (TRL) of technologies, alternative energy sources, and suitable infrastructure, all of which affect the cost of commodities and technologies. Therefore, evaluating these pathways and assessing their potential under different future scenarios and perspectives is essential. This study aims to assess the techno-economic and environmental feasibility of various energy transition options for the sugar industry, including HPs for energy efficiency improvement, hydrogen or bio-CH_4 fuel-switching, and complete electrification with electric boilers. Additionally, the potential for CO_2 capture (CC) is explored, despite limited research due to the relatively small scale of flue gas emissions from sugar production. A superstructure encompassing all options is modeled, and an evaluation based on two objective functions—total cost and total emissions—is conducted using mixed-integer linear programming (MILP).

2 PROCESS DESCRIPTION AND METHODOLOGY

2.1 Process Description

To assess diverse decarbonization options, a comprehensive Blueprint (BP) model of the sugar production process is developed encompassing various routes, as depicted in Figure 1. Energy and mass balances data are acquired from Best Available Techniques (BAT) document (Santonja et al., 2019) and open literature on sugar production process (Krajnc & Glavič, 2009; Morandin et al., 2011) and further validated alongside data from industrial plants. Additionally, modeling and simulations of pertinent utility systems are conducted in Aspen HYSYS software, employing Peng-Robinson and NRTL fluid packages.

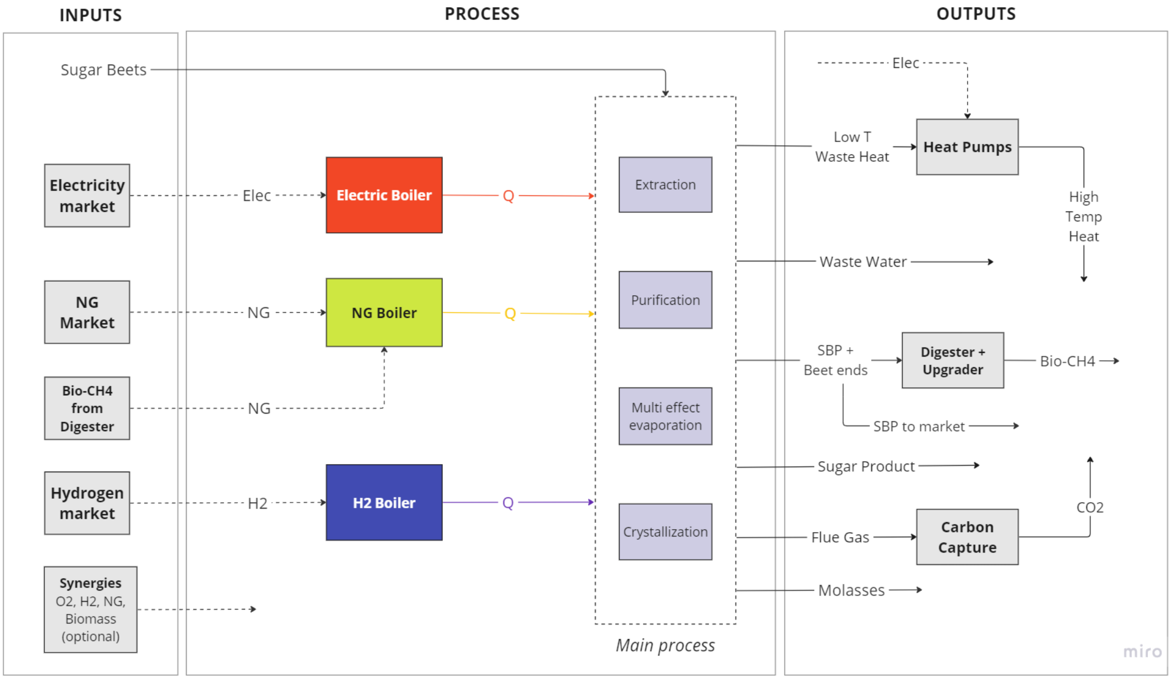

Figure 1: Superstructure of sugar production process incorporating various routes of production

Sugar production from sugar beets involves several key steps: extraction, purification, thickening, crystallization, and separation. Extraction occurs at around 50 – 70 °C where sugar beets are sliced into cossettes and flooded with hot water in a diffuser to release sucrose into raw juice. The wet SBP is pressed to reduce moisture, with press water recycled to the diffuser. The remaining SBP is dried into pellets for animal feed or to be used in biodigester to produce bio-CH_4. Next step is purification where raw juice is mixed with lime to precipitate impurities like multivalent anions and large organic molecules. CO_2 is added to convert lime into calcium carbonate, facilitating removal of non-sugar particles. This results in "thin juice" as a filtrate. This thin juice with 12-14% sugar content is evaporated in a multi-effect evaporation (MEE) step which operates at around 95 – 126 °C, resultantly producing thick juice with 65-70% sugar content. MEE uses steam efficiently, with low-grade steam leaving, which aids in crystallization. In crystallization, thick juice is seeded with sugar crystals and crystallized under vacuum at low temperature ranging from 35 – 65 °C to avoid decomposition. Crystallization occurs in stages, with three typical stages: A, B, and C. Crystals are separated from mother liquor in centrifugal machines. Sugar from the first crystallization stage (A) is dried, sorted, and packaged as white sugar. Run-off syrup from A is further processed in stages B and C to extract more sugar. Sugar from these stages is of lower quality and may be used for industrial purposes or as feed supplement for livestock or bioethanol production. Molasses, a byproduct, is also used for these purposes (Krajnc & Glavič, 2009). In the sugar production process, the demand for heating is typically fulfilled by high-temperature superheated steam generated by either a boiler or a combined heating and power (CHP) system. However, in our case, a CHP plant is not considered, as the aim is to utilize green electricity from the grid, sourced from offshore and onshore wind turbines, as well as solar panels, in future energy scenarios projected for 2030 or 2050. Therefore, in the base case configuration, a NG-fired boiler with an assumed efficiency of 80% for steam generation is employed, while electricity is imported from the grid. In an all-electric configuration, an electric boiler with 95% efficiency is utilized. In the event of fuel-switching, an H_2-fired boiler with 80% efficiency is employed to generate the required steam. Another alternative involves the valorization of sugar beet ends and SBP in a biodigester and biogas upgrader to produce bio-CH_4, which replaces NG sourced from the grid. Notably, in this configuration, the biogenic CO_2 is not factored into the total emissions calculation, as biowaste is generated and valorized on-site, resulting in net-zero emissions. Additionally, each configuration is equipped with option of utilizing supercritical HPs, to upgrade the waste heat available at lower temperatures. Lastly option of a monoethanolamine (MEA) based CC unit is incorporated with each configuration, which is capable of capturing 90% of CO_2 from flue gas with a capture cost of 80 €/t_{CO2}. An auxiliary heating system (utilizing same energy commodity as given configuration) is utilized to provide energy to the CC unit. The comprehensive superstructure, encompassing all configurations, is depicted in Figure 1.

2.2 Methodology

For the techno-economic analysis of each configuration discussed above, a Blueprint (BP) (Cervo et al., 2020) model of the superstructure is developed and written in LUA code. This BP entails all the mass and energy balances, CAPEX and OPEX, material and energy resources costs. This model is then utilized in OSMOSE Lua optimization framework (Yoo et al., 2015), which uses an MILP approach to identify the optimal route based on the given objective functions. The two objective functions employed for the evaluation are total specific cost (TSC) (€/t_{sugar}) and total specific emissions (TSE) (t_{CO2}/t_{sugar}) and the MILP problem to be solved is outlined in equations (1-4).

$$Annual\ CAPEX(u_s)_{n,i} = \left(CAPEX(u_{ref}) \cdot \left(\frac{S_0}{S_{ref}}\right)^{0.6} \cdot C_{BM} \cdot \frac{CEPCI_{2022}}{CEPCI_{ref}}\right) \cdot i \cdot \frac{(i+1)^n}{(i+1)^{n-1}} \tag{1}$$

$$Annual\ OPEX = \sum_{u \in units}\left(\sum_{e \in energy}\left(C_{e_u} \cdot \dot{Q}_{e_u}\right) + \left(C_{em_u} \cdot \dot{m}_{em_u}\right) + \sum_{m \in material}\left(C_{m_u} \cdot \dot{m}_{m_u}\right)\right) \cdot hrs \tag{2}$$

$$\min TSC\ \left(\frac{€}{t\ of\ sugar}\right) = \frac{Annual\ OPEX + Annual\ CAPEX}{ton\ of\ sugar\ produced\ per\ year} \tag{3}$$

$$\min TSE\ \left(\frac{t\ of\ CO_2}{t\ of\ sugar}\right) = \frac{\sum_{u \in units}\left(\dot{m}_{em_u}\right) \cdot hrs/1000}{ton\ of\ sugar\ produced\ per\ year} \tag{4}$$

In equation 1, (u) stands for unit, (S) for size of unit, (ref) for the reference unit in CAPEX calculations, and C_{BM} for the bare module cost factor encompassing direct and indirect expenses. For annualization of the CAPEX, a 40-year as lifetime "n" and a 3% discount rate "i" are considered. Moreover, in equation (2) "C" is for cost, "e" stands for energy source, "$\dot{Q}$" and "$\dot{m}$" for energy (kW) and mass (kg/h) flow rates, respectively, "em" for emissions and "hrs" for total operating hours, which are 8760 hours. For each configuration, the TSC and TSE act as KPIs for the evaluation along with specific energy consumption (GJ/t_{sugar}) as third KPI.

Moreover, to assess the proposed configurations, three distinct energy scenarios have been established: the 2023 reference scenario, the 2030 scenario, and the 2050 scenario. These scenarios influence the costs of H_2, NG, and CO_2 emission, which in turn serve as decision variables aimed at minimizing the objective function. It is important to note that these costs are assumptions and are utilized as weights, primarily to delineate the decision space and generate Pareto fronts. Moreover, the cost of NG is set constant, as the objective is to study the effects of variability of renewable sources. Table 1 presents the arbitrarily assumed costs associated with each energy commodity, as well as CO_2 emissions, for each scenario.

Table 1: Assumed costs of Electricity, H_2, NG and CO_2 emissions based on each scenario

Scenario	**CO_2 Cost (€/t_{CO2})**	**Electricity Cost (€/kWh)**	**H_2 Cost (€/kWh)**	**NG Cost (€/kWh)**
2023	70	0.2	0.2	0.037
2030	100	0.075	0.075	0.037
2050	150	0.05	0.05	0.037

3 RESULTS AND DISCUSSIONS

The superstructure outlining alternative configurations for the decarbonization of the sugar production process, as depicted in Figure 1, undergoes evaluation using MILP formulation across three distinct energy scenarios. In the reference scenario (2023), the TSC of the base case configuration, employing a NG-fired boiler, amounts to 124 €/t_{Sugar}. Furthermore, the base case configuration requires 6.39 GJ/t of NG and 0.52 GJ/t of electricity. The TSE associated with the base case configuration stand at 0.351 t_{CO2}/t_{Sugar}. Integrating the CC unit results in an 87% decrease in TSE. However, this comes with the penalty of a 9% increase in TSC and a 28% increase in total energy consumption. Additional cost results from the OPEX and CAPEX associated with CC unit, which is still higher than the cost reduction coming from the decrease in CO_2 emissions. As previously discussed, low-temperature waste heat around 70 °C is available during the process, suggesting that upgrading this waste heat via HPs could be a viable option. Figure 2 presents the grand composite curve of the base case configuration, with labels indicating different process units.

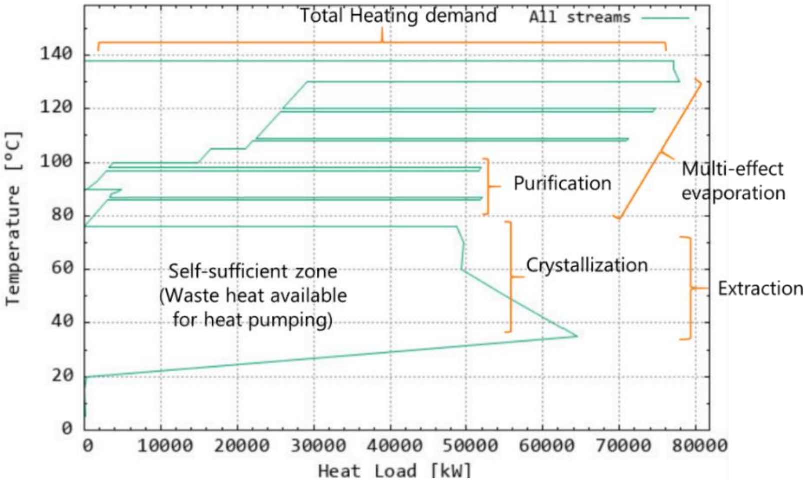

Figure 2: Grand Composite Curve of the main steps of a typical sugar production plant (base case)

It is evident from the figure, the waste heat below the second pinch point (78 °C) is available for upgrading, highlighting the potential application of HPs. After the implementation of HPs, the TSC decreases by 6.5%, accompanied by a 26% decrease in total energy consumption. This reduction results in a 33% decrease in TSE. The reduction in TSC comes from reduction in NG consumption and CO_2 emission costs, which is more significant than additional OPEX and CAPEX of HPs. The grand composite curve of the process following the application of HPs is depicted in Figure 3. Combining the base case configuration with HPs and CC unit results in further decrease of TSE to 96%, however it increases TSE 123 €/t_{sugar}, due to additional cost of CC unit, higher than just integration of HP.

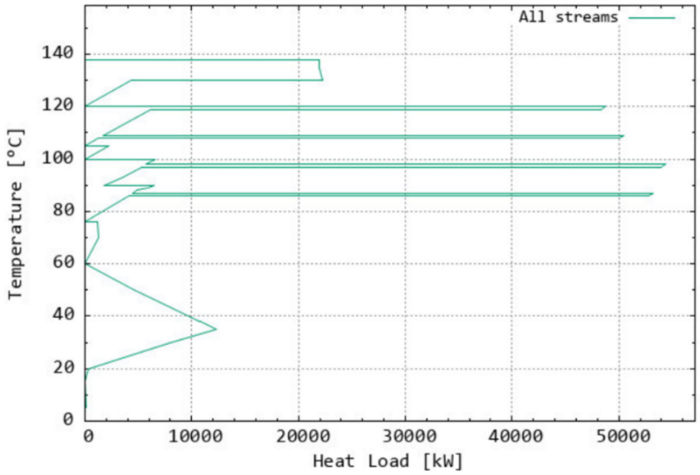

Figure 3: Grand Composite Curve of a sugar production process after recovering waste heat with the application of several HPs

Transitioning to the utilization of bio-CH_4 derived from the valorization of beet ends and SBP yields a TSC of 113 €/t_{sugar}, representing an 8.7% reduction compared to the base case, along with a TSE of 0.207 t_{CO2}/t_{sugar}, signifying a 41% decrease. Despite a 34% increase in electricity consumption sourced from the biodigester, the substantial reductions in TSC due to decreased NG import and CO_2 emissions remain noteworthy. The inclusion of a CC unit results in negative emissions of -0.01 t_{CO2}/t_{sugar}, albeit accompanied by additional NG and electricity consumption, thereby increasing the TSC to 124 €/t_{sugar}. Integration of HPs leads to a rise in electricity consumption, however the elimination of NG imports from the grid results in zero emissions. Combining this with a CC unit results in a net negative emissions of -0.117 t_{CO2}/t_{sugar}, albeit with additional electricity and bio-CH_4 consumption, consequently increasing the TSC. Following superstructure optimization, the most viable option in terms of TSC for the reference scenario is the utilization of bio-CH_4 with HP integration. However, concerning TSE, the optimal choice is bio-CH_4 with HP and CC unit integration. A tradeoff between the two objective functions suggests selecting the former option as the most optimal in the reference scenario. A Pareto front illustrating these results is depicted in Figure 4.

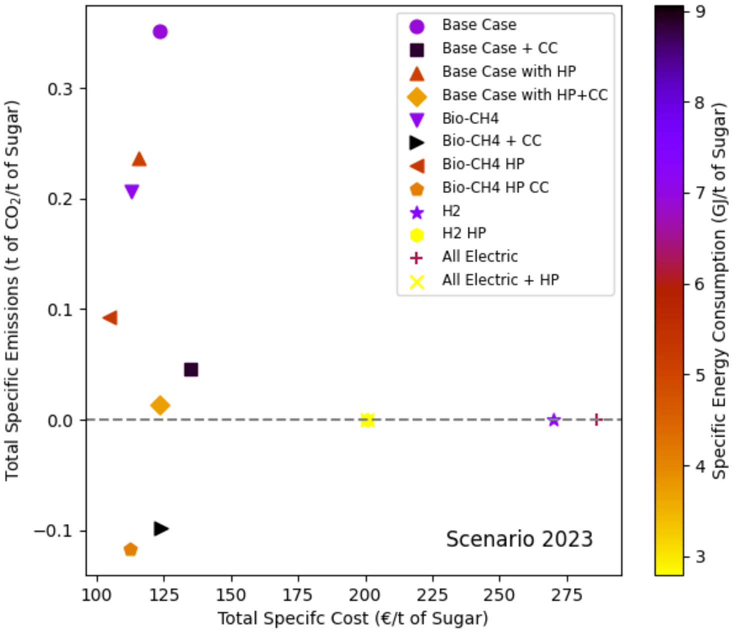

Figure 4: Pareto front for the reference scenario depicting TSC vs TSE. In the plot, base case = NG-fired boiler configuration, Bio-CH_4 = Bio CH_4-fired boiler configuration, H_2 = H_2-fired boiler configuration, All Electric = Electric boiler configuration, CC = CO_2 capture unit, HP = heat pumps

Notably, options involving the utilization of H_2 and electric boilers are deemed unsuitable due to the higher purchase costs of H_2 and electricity. In the case of an all-electric configuration, the electricity demand escalates to 92% higher than the base case.

In the 2030 scenario, the prices of electricity and H_2 are more favorable and reduced, assuming additional green energy influx from renewable electricity and H_2 projects. Additionally, an extra cost is imposed on CO_2 emissions (EnergyVille, 2023). The assumed prices, acting as decision variables, are provided in Table 1. In this scenario, the base case yields a TSC of 98 €/t_{sugar} with a TSE of 0.351 t_{CO2}/t_{sugar}. However, after analyzing the superstructure, the most suitable option emerges as the utilization of bio-CH_4 with the integration of HPs and a CC unit. Despite this configuration exhibits a 10% higher energy consumption compared to bio-CH_4 with just the integration of HPs, which ranks next, the TSC is still lower due to net negative emissions, further reducing costs. The Pareto front depicting the rankings of configurations for the 2030 scenario is presented in Figure 5. It is noteworthy that the decrease in the cost of electricity highly favors options associated with HPs. For example, the TSC of the NG boiler configuration with the addition of HPs is 43% lower than the base case. This cost reduction is also favored by an increase in CO_2 emissions cost. Furthermore, unlike the reference scenario, the options of the H_2 boiler and electric boiler with the integration of HPs turn out to be cheaper than the base case. Nevertheless, these configurations remain expensive without the integration of HPs. For the 2050 scenario, a further decline in energy commodity prices and an increase in the price of CO_2 emissions contribute to the base case configuration becoming costliest, with a TSC of 130 €/t_{sugar}. Interestingly, integrating a CC unit with the base case demonstrates relative suitability, resulting in an 11% reduction in TSC. This highlights that incorporating a CC unit to base case configuration may only become a viable option when higher prices for CO_2 emissions are implemented. Similar to the 2030 scenario, the integration of a bio-CH_4 system with HPs and CC units emerges as the most favorable option in 2050. This is attributed to effective energy management facilitated by HPs and the consequential reduction in CO_2 emissions achieved through the deployment of CC unit. Consequently, configurations involving HPs are further endorsed in the 2050 scenario. The Pareto front for the 2050 scenario, as depicted in Figure 6, reveals an intriguing trend: the decrease in commodity prices also favors the adoption of options such as H_2 and electric boilers. These alternatives demonstrate TSC reductions of 14% and 27%, respectively, compared to the base case. Moreover, integrating these configurations with HPs enhances their competitiveness in the ranking. Detailed results regarding energy consumption, TSC, and TSE for all three scenarios are presented in Table 2.

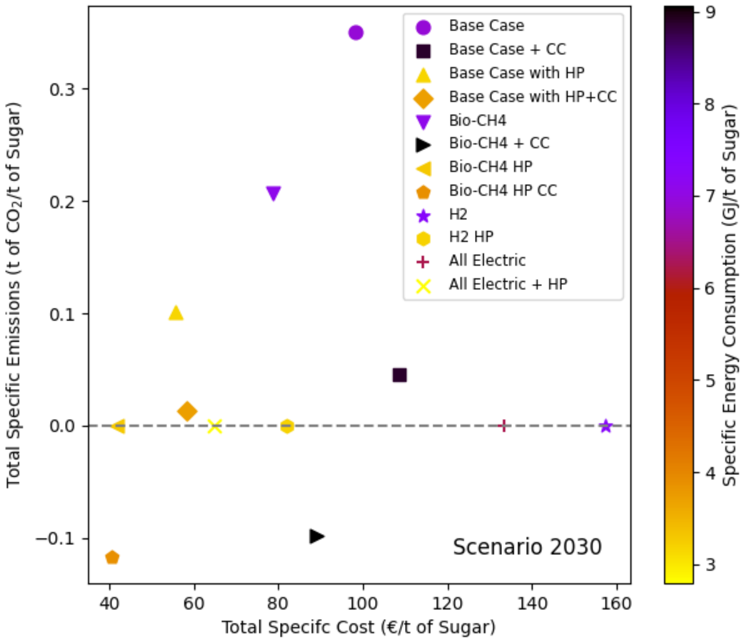

Figure 5: Pareto front for the 2030 scenario depicting TSC vs TSE. In the plot, base case = NG-fired boiler configuration, Bio-CH_4 = Bio CH_4-fired boiler configuration, H_2 = H_2-fired boiler configuration, All Electric = Electric boiler configuration, CC = CO_2 capture unit, HP = heat pumps

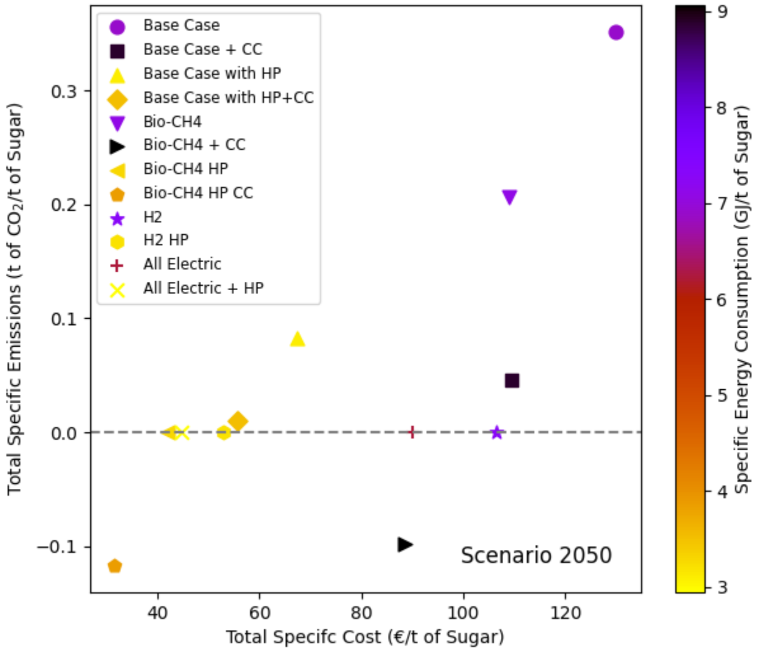

Figure 6: Pareto front for the 2050 scenario depicting TSC vs TSE. In the plot, base case = NG-fired boiler configuration, Bio-CH_4 = Bio CH_4-fired boiler configuration, H_2 = H_2-fired boiler configuration, All Electric = Electric boiler configuration, CC = CO_2 capture unit, HP = heat pumps

Table 2: Detailed results of energy resources consumption, TSE and TSA for all scenarios. In the table, NG = NG-fired boiler configuration, Bio-CH_4 = Bio CH_4-fired boiler configuration, H_2 = H_2-fired boiler configuration, All EL = Electric boiler configuration, CC = CO_2 capture unit, HP = heat pumps, EL = electricity, NG = Natural Gas

KPI	**NG**	**NG + CC**	**NG + HP**	**NG+ HP+ CC**	**Bio-CH_4**	**Bio-CH_4 + CC**	**Bio-CH_4 + HP**	**Bio-CH_4+ HP + CC**	**H_2**	**H_2 + HP**	**All EL**	**All EL + HP**
TSE (t_{CO2}/t_{Sugar})	0.351	0.046	0.102	0.013	0.207	-0.099	0	-0.117	0	0	0	0
NG demand (GJ/t)	6.39	8.34	1.85	2.37	3.76	5.71	0	0	0	0	0	0
EL Demand (GJ/t)	0.52	0.54	1.32	1.34	0.70	0.72	1.45	1.50	0.52	2.79	6.24	2.79
H_2 demand (GJ/t)	0	0	0	0	0	0	0	0	6.79	1.60	0	0
Bio-CH_4 (GJ/t)	0	0	0	0	2.63	2.63	1.85	2.37	0	0	0	0
TSC (€/t_{sugar}) (2023)	124	135	116	123	113	124	105	118	270	201	286	201
TSC (€/t_{sugar}) (2030)	98	109	56	58	79	89	42	41	157	82	133	65
TSC (€/t_{sugar}) (2050)	130	111	67	52	109	86	40	32	106	53	90	45

4 CONCLUSION

In this work, a superstructure optimization of different options for energy transition and decarbonization of the sugar production process is performed. It examines alternative energy supply options, such as utilization of H_2-fired boiler, digestion of bio-waste to produce bio-CH_4 and utilization of an electric boiler in case of complete electrification, by contrasting them with a traditional NG-based approach. Each option integrates HPs, upgrading the waste heat of the process, and a CC unit. To evaluate the superstructure, a MILP formulation is developed with TSC and TSE as the main objective functions. Moreover, total energy consumption is also calculated as an additional KPI. Furthermore, to solve the MILP problem, the OSMOSE Lua optimization framework is used. Three different scenarios are developed, namely the 2023 (reference scenario), 2030 and 2050 scenarios. These scenarios influence the costs of energy commodities such as H_2 and electricity and also the cost of CO_2 emissions, which behave as decision variables in the optimization problem.

From the results, in the case of the reference scenario (2023), the base case, utilizing an NG-fired boiler, has a TSC of €124/t_{Sugar} and emits 0.351 t_{CO2}/t_{Sugar}. Integrating a CC unit reduces emissions by 87%, but increases TSC by 9% and energy consumption by 28%. HPs show promise, reducing TSC by 6.5% and TSE by 33% through waste heat utilization. bio-CH_4 integration offers an 8.7% TSC reduction and 41% TSE decrease compared to the base case. The optimal solution for TSC is bio-CH_4 with HPs, while bio-CH_4 with HPs and CC units achieves the best TSE. A tradeoff between TSC and TSE favors the former option. Options involving H_2 and electric boilers are deemed less viable due to higher purchase costs of energy sources and increased electricity demand. For the 2030 scenario, favorable price reductions in electricity and H_2 and an increase in CO_2 emissions cost, significantly influence decision-making. Through evaluation of various configurations, the most favorable option emerges as utilizing bio-CH_4 with integrated HPs and a CC unit, resulting in net negative emissions and a lower TSC. The 2030 scenario highlights the importance of reduced electricity costs, particularly benefiting options associated with HPs. Integrating HPs with the NG boiler option leads to a substantial 43% lower TSC compared to the base case, supported by higher CO_2 emission costs. Configurations involving H_2 and electric boilers with HP integration are also found to be cost-effective, surpassing the base case. However, configurations lacking HP integration prove to be expensive alternatives. Lastly, for 2050 scenario, a further reduction in energy commodity prices and an increase in CO_2 emission costs result in the base case configuration becoming the costliest. Integrating a CC unit with the base case leads to an 11% reduction in TSC, suggesting that integration of CC unit into base case configuration may become suitable with higher CO_2 emission prices. Similarly to 2030, the option of integrating the bio-CH_4 system with HPs and CC unit emerges as the most favorable option. HP integration continues to be endorsed in the 2050 scenario, with configurations involving HPs showing significant TSC reductions. The 2050 scenario highlights a trend where decreased commodity prices favor options like H_2 and electric boilers, leading to TSC reductions of 14% and 27% respectively compared to the base case. Integrating these configurations with HPs further enhances their competitiveness.

In conclusion, selecting the optimal route requires balancing TSC and TSE. Additionally, considering the uncertainty in energy commodity costs, specific energy consumption also serves as a useful metric in this regard. The integration of HPs in sugar production processes is crucial for sectoral decarbonization, particularly with the expected decrease in renewable electricity prices. Additionally, valorising on-site biowaste shows promise in reducing sectoral carbon footprint. Implementing appropriate policies to manage beet ends and SBP waste for biogas/bio-CH_4 production and finding alternative sources for animal feed is essential for the energy transition. Furthermore, incorporating CC units may become a viable option with anticipated higher taxes on CO_2 emissions. H_2 and electric boilers for steam generation are feasible only when coupled with HPs or under favourable commodity price conditions. Future research will explore additional configurations, such as CHP plants for process power, and include the valorisation of molasses for bioethanol production to comprehensively evaluate a complete sugar refinery. Furthermore, within the TRILATE project, these enhancements and evaluation methodologies will be extended to other industrial sectors.

NOMENCLATURE

BM	Bare module
CAPEX	Capital expenditures
C	Cost
hrs	Hours
i	Discount rate
$\dot{m}$	Mass flow rate
n	Lifetime of plant
OPEX	Operating expenditures
$\dot{Q}$	Energy flow rate
S	Size of the unit
TSC	Total specific cost

TSE	Total specific emissions
u	Unit
Subscript	
e	energy
em	emissions
m	material
ref	reference unit

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