

Project description
Modelling, optimisation, design
and analysis of integrated energy systems

Thermo-environomic analysis of a cider production facility and heat pumping

Eduardo Pina¹, Du Wen¹, and François Maréchal^{*1}

¹*Industrial Process and Energy Systems Engineering (IPESE), École Polytechnique
Fédérale de Lausanne*

Spring semester 2024

Abstract

The goal of this project is to perform the thermal, economic, and environmental analysis of a cider production facility. The students are required to apply the knowledge acquired during the course. Each chapter is related to one day of the course. The students will be guided by the course assistants.

^{*}francois.marechal@epfl.ch

Project description

An investor wants to integrate a cider production facility next to a city, as shown in Figure 1. In the cider production facility there is an existing bottling process which makes use of recycled glass bottles (see the process description in Day 1). The investor would like to investigate the following questions:

- How to mitigate the CO₂-equivalent emissions and the energy and water usage related to the process?
- Are there possibilities of industrial symbiosis (e.g. developing a district heating)?
- Is it better to recycle the glass bottles (case A) or to invest in a PET bottle production facility from polyethylene pellets (case B)?

In order to answer these questions you will:

- Improve the energy performance of the process (for cases A and B) by applying nonlinear programming (NLP);
- Use life cycle assessment (LCA) to compare environmental performances;
- Use utility integration and multiperiod optimization in combination with district energy modeling;
- Apply interactive optimization techniques in order to account for uncertainty.

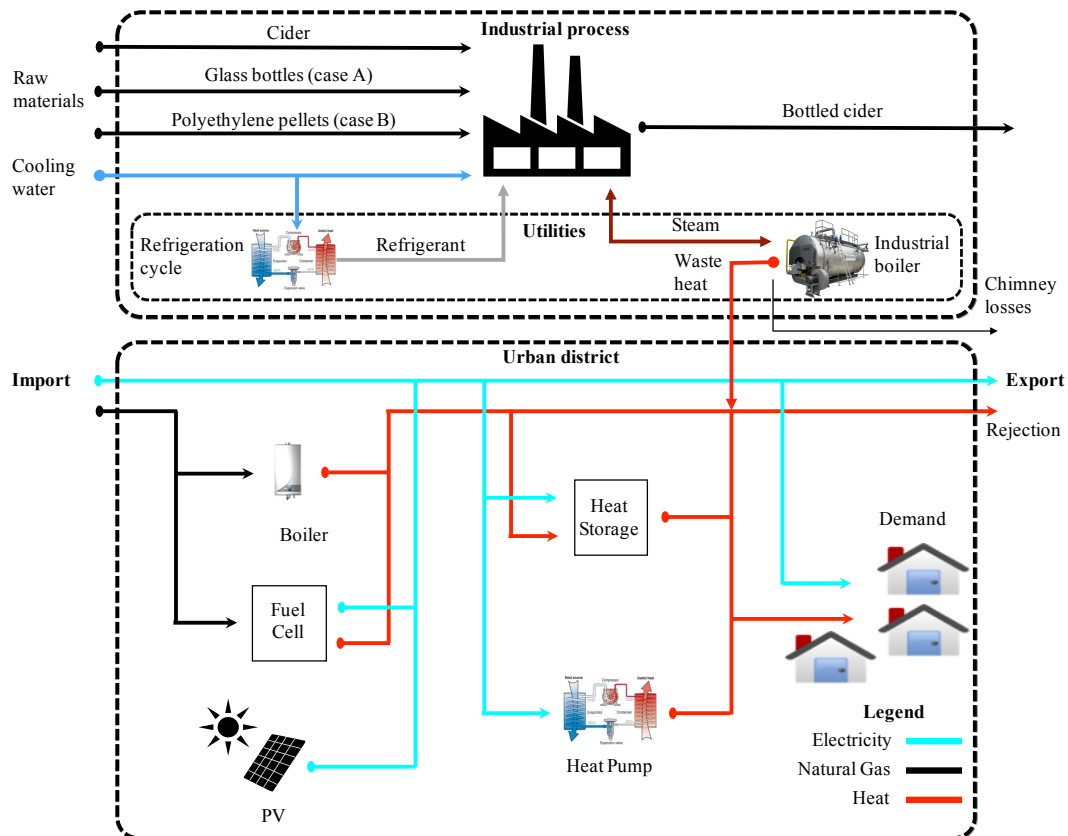


Figure 1: Integrated system consisting of industrial plant and urban district

Day 1. Heat recovery and $\Delta T_{\min}$ optimization

The bottling process of the cider plant should be optimized in terms of energy efficiency. Therefore your help is required for designing a heat recovery network and optimizing the minimum approach temperature $\Delta T_{\min}$ in the heat exchangers. In Figure 2 the existing process is displayed. Use the information found in Figure 2 and Table 1 to solve the optimization problem. The two target temperatures are a process requirement. The temperature after bottle filling is bound to be above 70°C . Additionally, the inlet temperature of the bottles cannot be altered. Questions 1-7 provide guidance to solve the exercise.

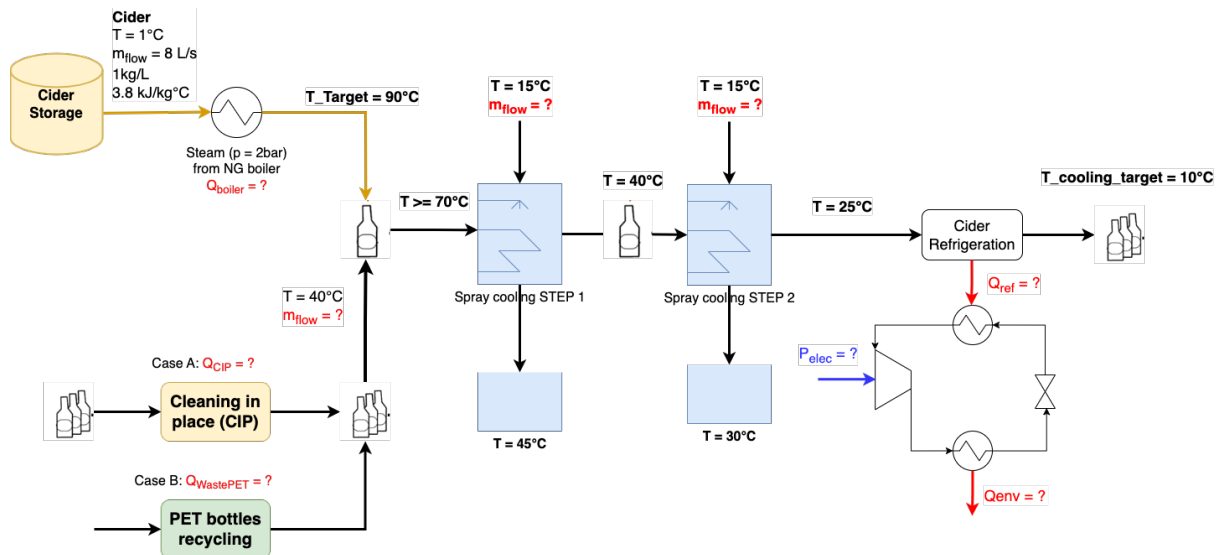


Figure 2: Bottling process (numbers in black refer to the current case).

- Q1. Open the .mod file and try to run it. Then add the variables, constraints and parameters needed to optimize the heat exchanger network.
- Q2. Calculate the mass flow rate of bottles entering the bottling process (glass or PET).
- Q3. What is the natural gas consumption in the steam boiler of the current case and the optimized case?
- Q4. What is the spray cooling (1 and 2) consumption in current case and in the optimized case?
- Q5. What is the load of the refrigeration cycle in both cases?
- Q6. What are the cost savings of the optimized case?
- Q7. What is the waste heat available in the boiler's exhaust gases? How much heat could be recovered for integration with an urban district? Assume that the exhaust gases below 122°C cannot be used by the process, but could be provided to a district heating network (DHN). Exhaust gases below 60°C are lost in the chimney.

Additional recovery and integration

The responsible engineer decided to avoid waste production in the plant premises. For a production rate of 8 L/s of cider, 16 kg/s of Swiss apples are required, generating 8 kg/s of

Table 1: Input data

Resources			
Natural gas price	CHF/kWh	0.06	
Water price	CHF/m ³	0.01	
Electricity price	CHF/kWh _{el}	0.15	
Bottles specifications (500 ml)		CASE A (glass bottles)	CASE B (PET bottles)
Weight	g	370	80
Heat capacity	kJ/(kg K)	0.75	1.67
Heat capacity after bottling	kJ/(kg K)	2.6	3.7
Temperature of empty bottles	°C	40	40
Temperature of empty bottles after pre-rinsing	°C	56	-
Temperature of empty bottles after soda-bath	°C	75	-
Useful information			
Operating hours	hr/yr	3000	
Boiler efficiency based on lower heating value	%	85	
Refrigeration cycle COP	-	3	
ΔT_{min} of all heat exchangers	°C	2	
Convective heat transfer coefficient	W/m ² K	500	
Interest rate	%	8	
Life time of heat exchanger	yr	20	
CEPCI	-	400; 562	2000; 2017 (respectively)
Logarithmic mean temperature approximation	eq. (8)	[2]	
Heat exchanger cost (including boiler)	CHF ₂₀₀₀	$750(A)^{0.7}$	A , area in m ²
Heat pump cost	CHF ₂₀₀₀	$3400(P_{el})^{0.85}$	P_{el} in kW
Bare module factor	4.74 (heat exchanger); 2 (boiler); 2.9 (compressor); 2 (heat pump)		
Fixed input data (in optimization)			
Juice input data (T, m, rho, cp)			
Temperature of empty bottles	°C	40	
Temperature of cooling water	°C	15	
Temperature outlet of boiler (pasteurization)	°C	90	
Temperature of filled bottles (before cooling)	°C	≥70	
Temperature of cooled juice bottles	°C	10	

Day 2. Combined heat and water optimization: Bottle cleaning

As part of the cider production process shown in Figure 2, there is an existing cleaning-in-place (CiP) facility that is used for recycling the glass bottles, as described in [3]. The current state of the process is shown in Figure 4.

Current situation: “... The washing system mainly aims at preparing the packaging materials (mainly bottles) before filling them with cider. This process is considered as a continuous operation. The bottles are successively pre-rinsed, then washed with soda and rinsed in successive baths again, before being filled. The temperature of the baths is maintained by steam injection. The final rinsing is done with clear water at 15 °C. Water of the final bath rinsing is recuperated and sent to the pre-rinsing bath, recovering heat from the bottles that are cooled down in the last bath. ...” [3]

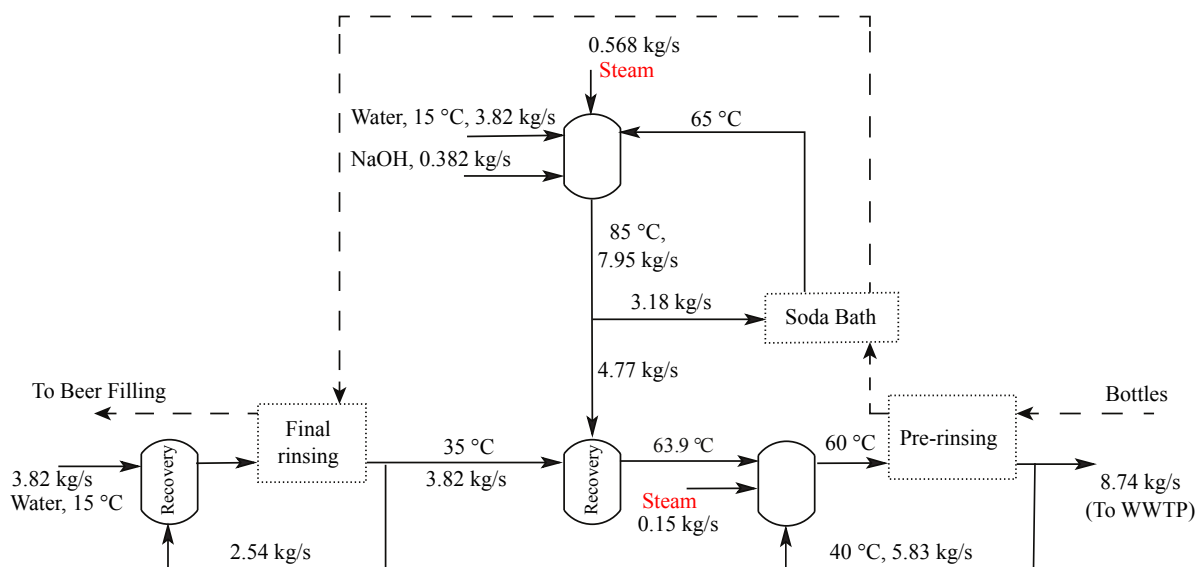


Figure 4: CiP for glass bottles (adapted from [3])

As it can be observed from Figure 4, the wastewater is being released at 40 °C. We will assume that the bottles enter the cleaning process at 15 °C, and are heated up in pre-rinsing and soda bath to a temperature which is not measured. This heat is further recovered in the final rinsing by heating up the water. We further assume that the final temperature of the bottles is 40 °C (entrance temperature to the bottling process shown in Figure 2). The goal is to minimize the hot utility (i.e. steam) and fresh water consumption, and wastewater generation. The main challenge in this problem is the fact that water has two duties, i.e. removing contamination from the dirty bottles entering the CiP and heating them up or cooling them down. Figure 5 provides additional input data of the CiP:

- Maximum inlet (C_{in}^{max}) and outlet contamination level (C_{out}^{max}) in each water units given in *ppm* (part-per-million $\sim mg/kg$).
- Mass load (L) that has to be removed in each unit [g/s]

In order to solve this problem, a linear programming (LP) model can be formulated by following steps below:

- First, note that the data in Figure 4 and Figure 5 are for 19.1 kg/s of cider production. Your problem is defined for 8 l/s of cider (Figure 2). You need to change the appropriate parameters to address this case. (*Hint: you need to multiply some parameters by this ratio!*)
- What is the current consumption of fresh water and steam? How much wastewater is being generated?
- Think of the main problem to be formulated, i.e. what are the main water units (i.e. consumers, producers) that have to be considered in the model? (*Hint: The previous paragraph has the answer. Do not forget your utilities!*)
- Knowing the mass flow rate of water in the main three units together with their inlet and outlet temperatures, i.e. the heat load of water streams, calculate heat exchange efficiencies (in pre-rinsing, soda bath, and in final rinsing). See Table 1 for input data. You will use these efficiencies as input parameters of your model.
- Generally, one can consider two types of heat exchange in such a water network:
 - **Indirect heat exchange:** The heat transfer occurs between two fluids that are separated by a barrier or intermediary material, i.e. shell and tube heat exchanger.
 - **Direct heat exchange:** The heat transfer occurs between two fluids or substances that are in direct contact with each other via non-isothermal mixing of water streams.

At this level you need to propose a network of indirect heat exchanges (to avoid having integers in your model; the indirect heat exchanges will be taken care of in the water network that you will write) for heat and water recovery. Follow the steps in the provided files to construct your model. (*Hints: i) It is always good to sketch this network first on a piece of paper! ii) Don't forget the wastewater that should be cooled down to 20 °C!*)

- **General assumptions and formulations:**

- Hot utility is assumed to be steam at 2 bar at saturated vapor state.
- Contamination levels of fresh water and steam are negligible.
- For wastewater, one can assume a very high contamination level.
- No water can be recycled from the soda bath into final rinsing!
- Non-isothermal mixing at the inlet of water unit operation (**WUO**) u :

$$\sum_{j=1}^{\mathbf{WUO}} \dot{m}_{j,u} \cdot T_{j,out} = \dot{m}_u T_{u,in} \quad \forall u \in \mathbf{WUO} \quad (1)$$

- Mass transfer in each **WUO** u (for single-contaminant problem, as in your case, this equation can be linearized by fixing the contamination levels to their maximum values and changing the equality to inequality (which way?!)) (*Hint: In modelling the equation, pay attention to unit conversions!*):

$$\sum_{j=1}^{\mathbf{WUO}} \dot{m}_{j,u} \cdot C_{out,j} + L_u = \dot{m}_u C_{out,u} \quad \forall u \in \mathbf{WUO} \quad (2)$$

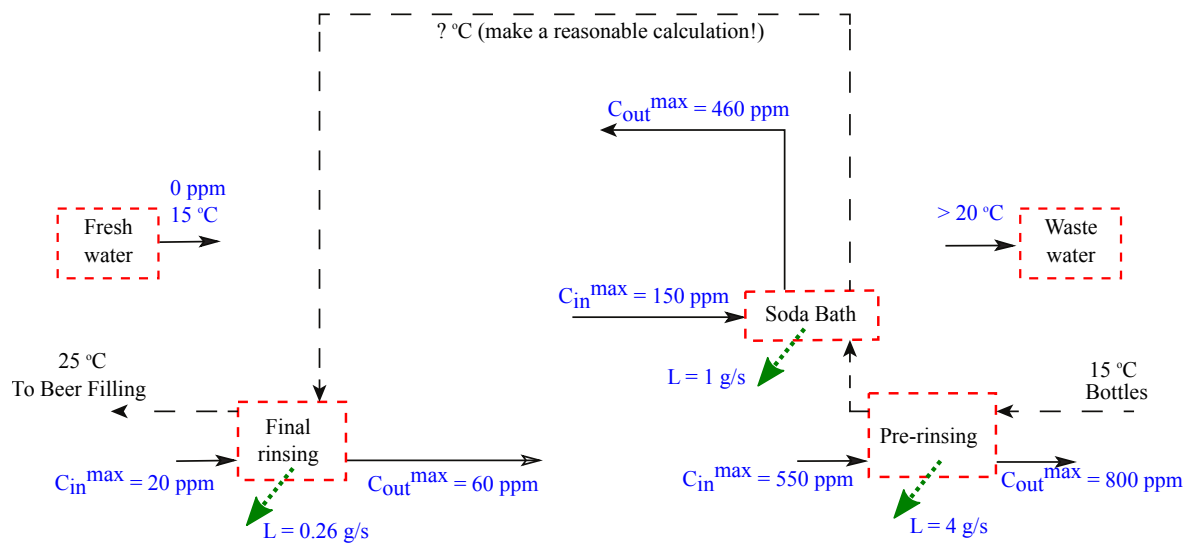


Figure 5: Input parameters of CiP

Day 3. LCA analysis of the process

You are now asked to perform a LCA analysis of the process:

- Q1. Determine the following for the baseline glass production system:
- Define the functional unit.
 - Describe the system boundaries identifying all relevant activities (unit processes) pertaining to the company gate-to-gate and the cradle-to-gate sub-systems and the full cradle to grave system.
 - Identify the intermediary flows.
 - Calculate the reference flows, scaling up the intermediary flows to the functional unit.
 - Calculate the LCA profile.
 - Interpret results identifying the most contributing activities to the overall impact score.
- Q2. Calculate the LCA profile for the optimized glass production system and discuss the mitigation potential of the optimized system on GHG emissions and the other environmental indicators.
- Q3. Calculate the LCA profile for the alternative PET system and compare its profile with the glass system.
- Q4. How would you model the heat recovery from the waste heat coming from the boiler (utility) for integration in a urban district? Answer by a qualitative reasoning by drawing the expanded system boundary.
- Q5. Add equations in the model of the process to calculate the GHG impact of the system as an additional result of the process. It is recommended to use the results you have already calculated and have the option to use the glass system, PET system, or a combination of the two.

LCA input data and assumptions:

- Glass bottle transport distance to the cider facility: 500 km.
- Average cider distribution distance: 100 km.
- Natural gas and electricity demand of the bottling facility:
 - Baseline (non optimized scenario): 5043 kW_{NG} and 180 kW_{el}.
 - Optimized scenario: 2446 kW_{NG} and 120 kW_{el}.
 - PET scenario: 1161 kW_{NG} and 106 kW

Table 2: LCA data

Ecoinvent cradle-to-gate process		IPCC 2013 climate change GTP 100a [kgCO ₂ -eq.]	IMPACT 2002+ ecosystem quality [PDF·m ² ·yr]	IMPACT 2002+ human health [DALY]	IMPACT 2002+ resources [MJ]
Polyethylene terephthalate, granulate, bottle grade [RER] production Alloc Rec, S	kg	2.79E+00	4.51E-01	6.00E-06	7.75E+01
Stretch blow moulding [RER] production Alloc Rec, S	kg	1.26E+00	2.25E-01	8.08E-07	2.56E+01
Electricity, medium voltage [CH] market for Alloc Rec, S	kWh	8.74E-02	2.72E-02	5.47E-08	8.39E+00
Heat, central or small-scale, natural gas [CH] heat production, natural gas, at boiler condensing modulating <100kW Alloc Rec, S	MJ	6.65E-02	2.12E-03	1.54E-08	1.26E+00
Transport, freight, lorry 16-32 metric ton, EURO5 [GLO] market for Alloc Rec, S	tkm	1.64E-01	1.12E-01	1.19E-07	2.71E+00
Transport, freight, lorry with reefer, cooling [GLO] market for Alloc Rec, S	tkm	1.21E-01	9.59E-02	1.32E-07	2.03E+00
Packaging glass, white [CH] production Alloc Rec, S	kg	5.81E-01	1.11E-01	4.44E-07	1.05E+01
Inert waste [CH] treatment of, sanitary landfill Alloc Rec, S	kg	7.95E-03	3.55E-03	1.30E-08	2.55E-01
Waste polyethylene terephthalate [CH] treatment of, municipal incineration Alloc Rec, S	kg	2.02E+00	1.11E-02	4.33E-07	1.42E-01
PET - recycling	kWh/kgPET		0.6		

Day 4. Integration with an urban district: multi period renewable utility analysis and heat pumping

In the urban district there are 100 houses. You are given the model of one of these houses, which is schematically represented by the household energy system in Figure 1. The mixed-integer linear programming (MILP) formulation is detailed in [5]. Given the monthly energy demand, the cost and efficiency data of the available energy conversion technologies, and the price of energy resources, the model outputs the optimal investment and operation strategy. The objective is the minimization of the total annual cost of the energy system.

- Q1. The owner of the house wants to go green. Thus, they are evaluating the option of installing photovoltaic panels on the roof. Add this option to the model formulation, using the data in [5].
- Q2. Add constraint (9) in [5] to the model formulation and run the model in AMPL. *Ops!* There is an error! Can you identify it? Fix it and move to the next question.
- Q3. As you found out in Day 1, there is an excess of heat available from the industrial process. The municipality has thus decided to build a network to distribute this heat to the houses via district heating. How does the optimal solution change if you add this option? You can assume that each household can use 1% of the total waste heat available (106 kW).
- Q4. As you found out in Day 1, there is the possibility of using biogas from the biodigester and catalytic hydrothermal gasification processes. Add this option to the model formulation and evaluate the impact on the optimal solution. Make the necessary assumptions.
- Q5. The family's child is getting married and decides to build a new house next to their parent's house. As they care about energy efficiency, they install a low-temperature floor heating system (35°C) for the new house. The energy demand profile of the new building is identical to the old one. They are considering the installation of a ground source heat pump (GSHP).
 - a) Add the GSHP and the new house to the model. The GSHP operates between 10°C and 35°C, and its exergy efficiency is $\eta = 0.5$. The other features are identical to the heat pump already considered in the model. The GHSP has a low temperature (LT) heat output, compatible with the temperature levels of the new house. The old house and the other energy technologies have a high temperature (HT) heat demand and production, respectively. Electricity for the new house is supplied by the same technologies already supplying the old house.
 - b) The family is evaluating if the same energy technologies can be shared between the two houses. How does the solution changes if accounting for the possibility of cascading heat from HT to LT?
- Q6. The greenhouse gas emissions of Natural Gas (NG) is 0.267 kgCO₂-eq./kWh_{NG} [6]. The monthly emission factors of the electricity imported from the grid are given in Table 3; note that it includes an additional value corresponding to an extreme situation.
 - a) Calculate the total CO₂-eq. emissions of the energy system.

Table 3: Monthly electricity emission factors

Month	Emission factor, kgCO ₂ -eq/kWh
Jan	0.18249
Feb	0.19364
Mar	0.12378
Apr	0.09727
May	0.05376
Jun	0.04082
Jul	0.03149
Aug	0.02863
Sep	0.08379
Oct	0.09731
Nov	0.15323
Dec	0.11699
Extreme	0.29046

- b) MILP models have only one objective. However, the family wants to assess the trade-off between emissions and cost. How can this be done? Generate a graph showing this trade-off.
- c) What are the minimum yearly emissions that can be achieved in the system? Which factor needs to be changed to further decrease this value?
- d) As shown in Table 3, the emission factors of the electricity from the grid can have significant changes over the months of the year. How is the system managing the CO₂ emissions with the grid?

References

- [1] Rafael Castro-Amoedo, Nicolas Morisod, Julia Granacher, and François Maréchal. The Role of Biowaste: A Multi-Objective Optimization Platform for Combined Heat, Power and Fuel. *Frontiers in Energy Research*, 9:417, 2021.
- [2] JJJ Chen. Comments on improvements on a replacement for the logarithmic mean. *Chemical Engineering Science*, 42(10):2488–2489, 1987.
- [3] François Marechal, Anurag Kumar Sachan, and Leandro Salgueiro. 27 - Application of Process Integration Methodologies in the Brewing Industry A2 - Klemeš, Jiří J. In *Handbook of Process Integration (PI)*, Woodhead Publishing Series in Energy, pages 820–863. Woodhead Publishing, 2013.
- [4] Alberto Mian, Adriano V. Ensinas, and François Marechal. Multi-objective optimization of SNG production from microalgae through hydrothermal gasification. *Computers & Chemical Engineering*, 76:170–183, May 2015.
- [5] Stefano Moret, Michel Bierlaire, and François Maréchal. Robust Optimization for Strategic Energy Planning. *Informatica*, 27(3):625–648, November 2016.
- [6] Stefano Moret, Emanuela Peduzzi, Léda Gerber, and François Maréchal. Integration of deep geothermal energy and woody biomass conversion pathways in urban systems. *Energy Conversion and Management*, 129:305–318, December 2016.