IEA HPT Annex 58
High-Temperature Heat Pumps

WEBINAR ON HIGH TEMPERATURE HEAT PUMPS

7 NOVEMBER 2024

Web-based integration tool:

Design and demonstration case studies

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Outline

- Objectives and relevance
- Product profile
- Tool workflow for process integration and pinch analysis
- OSMOSE backend algorithm
- Data input interfaces: Excel-based and FlexiCode
- HP superstructure and ETs database
- Simplified GUI
- Typical results, reporting and validation
- Examples of use
- Conclusions and path forward

Objectives and relevance

Objectives

- To introduce a web-based decision support tool for the design and integration of industrial high-temperature heat pumps,

- To design a flexible, open-source tool for modeling, analyzing, and documenting the energy integration results of industrial processes.

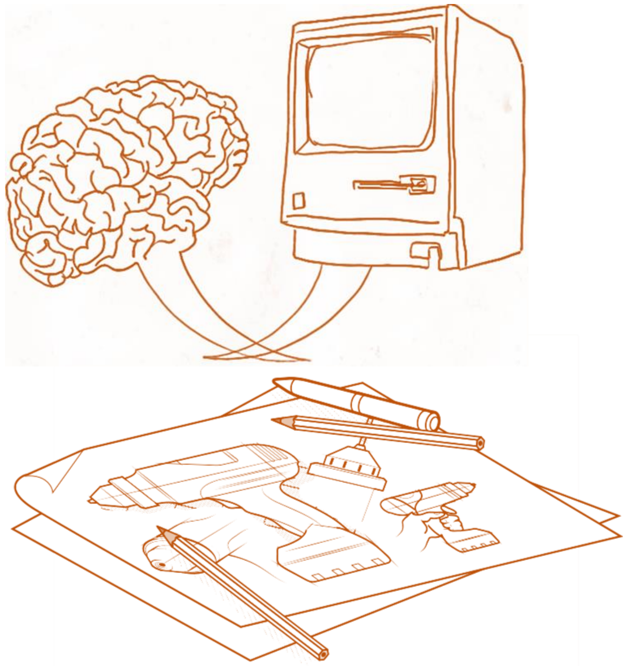
To inform end-users about the importance and benefits of the application of process integration techniques to the industrial processes

Relevance and challenges

- Increasing number of technological options and operating conditions,
- A comparative analysis requires a suitable modeling, optimization, visualization and reporting tool,
- Lack of intuitive, open-source tools to develop fast and accurate PAs.

Product profile

- HTHP workshop roundtable → survey for tool design and technology transfer.
- Generate and evaluate options (sub- or optimal) at variable conditions and competing techs → tradeoffs opex/capex.
- Check for possible integration errors → misplaced utilities or missed waste heat recovery opportunities.
- Improved data mngmt → centralized, updatable, trackable access to technical data in open-source formats (.csv, .json).
- Excel is widespread in the industry → ease end-users opt-in, but enable flexibility and comms with in-house software.
- Automatic framework → visualization, energy integration, and thermodynamic properties calculations *all-in-one*.
- Concerns about costs → software licenses, limited accessibility to algorithms, and reduced flexibility.
- Web-friendly reporting → Portable document format (PDF) and interactive hypertext markup language (HTML) files.
- Engine hosted at EPFL servers or local execution → support extensibility & confidentiality.



Tool workflow for PI and PA

- Process data from audits is input via Excel template, flowsheeting software or by directly coding (Python).

- Vendors’ data, incl. Ts, T lift, COP and capacity to assess commercial solutions.

- Open-source libraries (e.g. Coolprop) calculate thermodynamic properties.

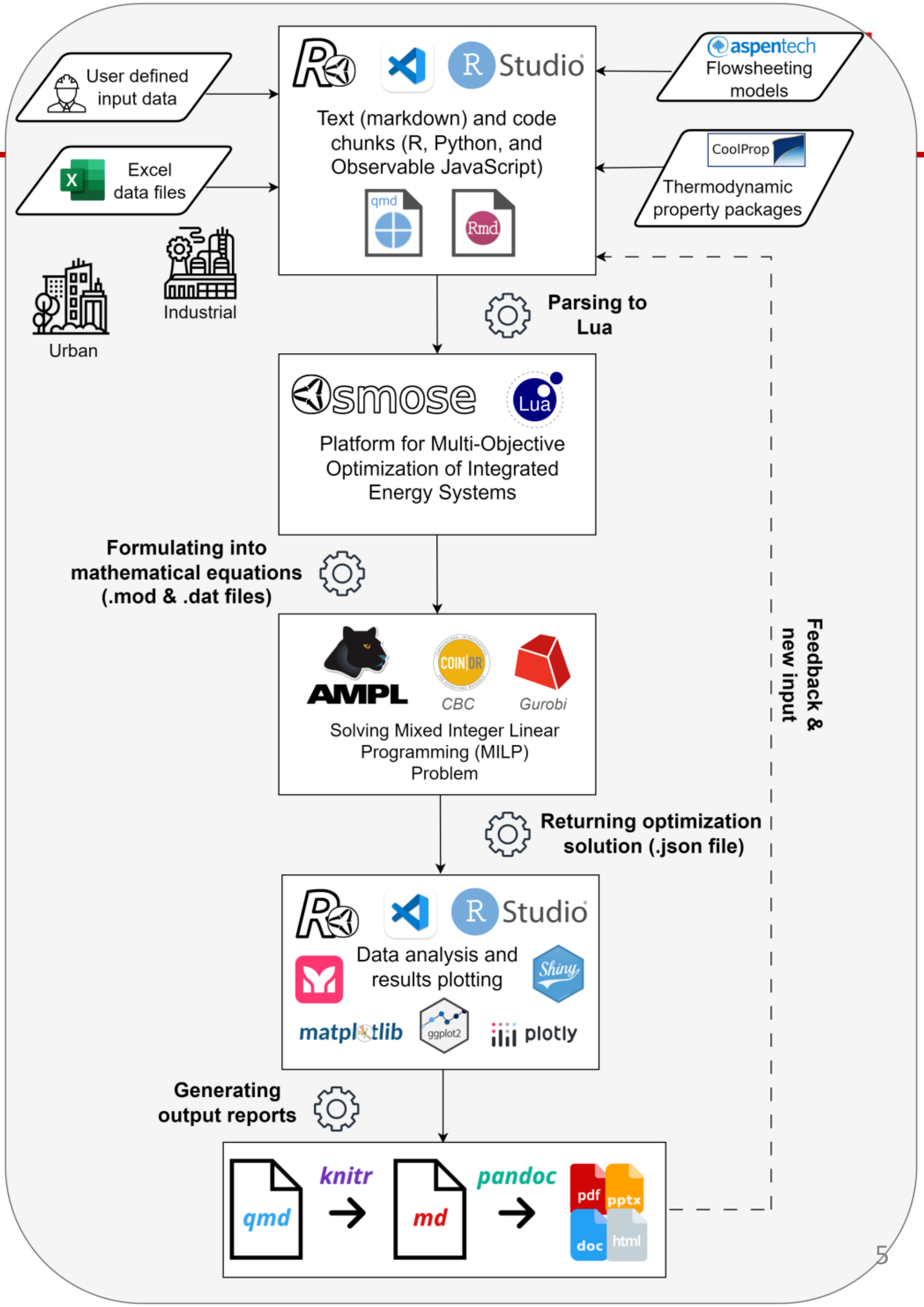
- Frontend for data input and OSMOSE engine execution, solves synthesis and optimization problem.

- .json output file with information needed to visualize and calculate KPIs.

- User-friendly .html report summarizes problem definition, assumptions, and PI/PA results (tables, plots, etc.) in a structured and shareable format.

- Pinch point(s) and penalized heat exchanges are spotlighted. Actions towards better integrating the energy systems can be investigated.

- Feedback loop to improve features of utility systems. HP superstructure can be refined.



User defined input data

Excel data files

Urban

Industrial

aspentech Flowsheeting models

CoolProp Thermodynamic property packages

Text (markdown) and code chunks (R, Python, and Observable JavaScript)

Parsing to Lua

osmose

Platform for Multi-Objective Optimization of Integrated Energy Systems

Formulating into mathematical equations (.mod & .dat files)

Solving Mixed Integer Linear Programming (MILP) Problem

Returning optimization solution (.json file)

Data analysis and results plotting

Generating output reports

Feedback & new input

OSMOSE backend algorithm

- (R)OSMOSE → Rmarkdown-based OSMOSE - Multi-Objective Optimization of Integrated Energy Systems Process integration tool developed at IPESE group in EPFL.

- The web-based decision tool relies on Pinch Analysis and uses a superstructure-based mixed integer linear programming (MILP) optimization algorithm.

- (R)OSMOSE selects the optimal energy technologies and utility systems to supply the energy demands with a minimum overall production cost, including capital and operational expenditures.

- Superstructure of competing utilities (e.g. furnace, electrical heater, engines, water cooling, refrigeration, **heat pumps**, photovoltaic systems and decarbonization technologies, such as biomass, CCS, etc.).

- Integrates various software and tools: (i) database handling routines (.csv and .json), (ii) thermodynamic libraries (Aspen, Coolprop), (iii) optimization suites (AMPL), and (iv) data visualization (GNU Plot, Plotly).

Data input interfaces

- Application of Pinch Analysis requires info of mass flows, thermodynamic properties, and supply and target temperatures of relevant streams.

- Data input via:

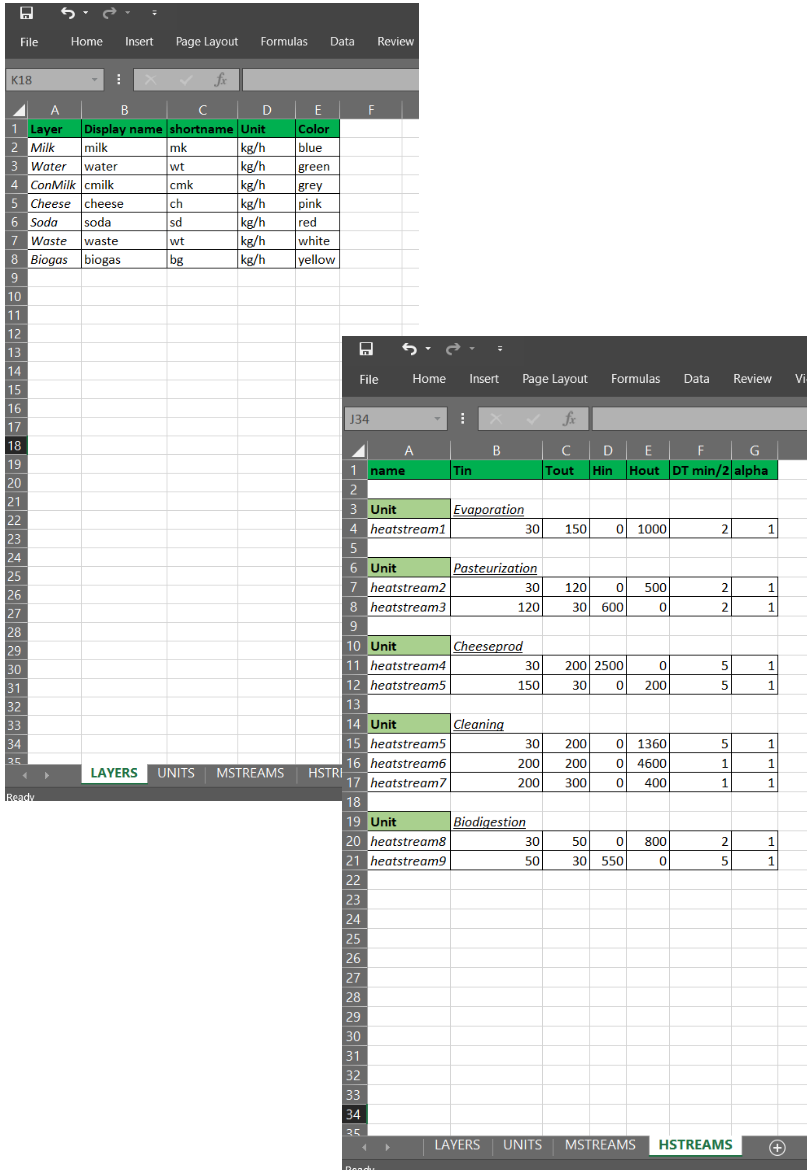
(i) manual insertion of hot and cold streams in FlexiCode,

(ii) imported from either Excel

(iii) flowsheeting software.

- Data can be collected on-site in an acquisition OPC (Open Platform Communications) servers, either in .json or .csv format (or compatible formats).

Excel-based data input



Layer	Display name	shortname	Unit	Color
Milk	milk	mk	kg/h	blue
Water	water	wt	kg/h	green
ConMilk	cmilk	cmk	kg/h	grey
Cheese	cheese	ch	kg/h	pink
Soda	soda	sd	kg/h	red
Waste	waste	wt	kg/h	white
Biogas	biogas	bg	kg/h	yellow

name	Tin	Tout	Hin	Hout	DT min/2	alpha
Unit	*Evaporation*					
heatstream1	30	150	0	1000	2	1
Unit	*Pasteurization*					
heatstream2	30	120	0	500	2	1
heatstream3	120	30	600	0	2	1
Unit	*Cheeseprod*					
heatstream4	30	200	2500	0	5	1
heatstream5	150	30	0	200	5	1
Unit	*Cleaning*					
heatstream5	30	200	0	1360	5	1
heatstream6	200	200	0	4600	1	1
heatstream7	200	300	0	400	1	1
Unit	*Biodigestion*					
heatstream8	30	50	0	800	2	1
heatstream9	50	30	550	0	5	1

Layers are relevant for ensuring mass and energy balances and for costing fuel, electricity, and feedstock. Specific costs of grids can be varied.

Energy technology (ET) are one or multiple process or utility units with connection layers. From single operation units to full industrial plants.

Mass streams/Resource streams, i.e. material and electricity flowing through layers in the energy integration problem.

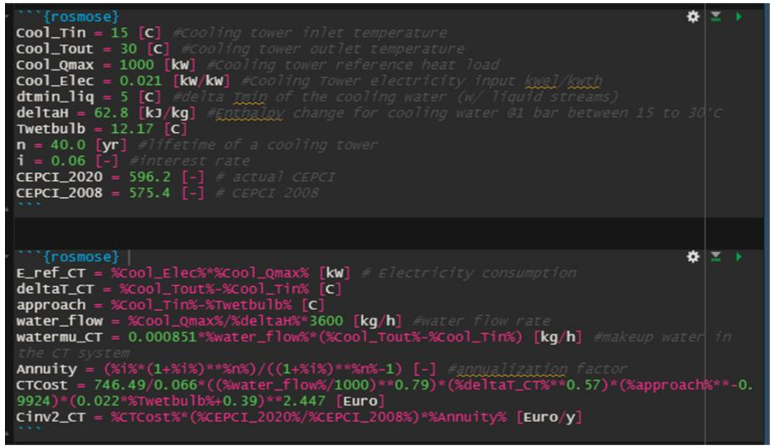
Heat streams defined by inlet and outlet temperatures (°C) and enthalpies (kJ/kg) or, alternatively, mass flow (kg/h) and heat capacities (kJ/kg K), or heating and cooling duties (kW).

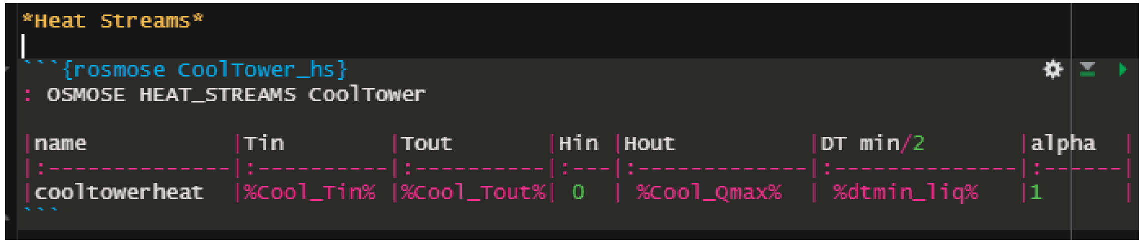
Excel template

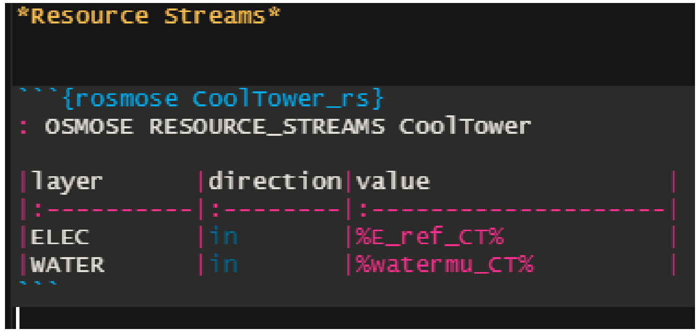
FlexiCode GUI

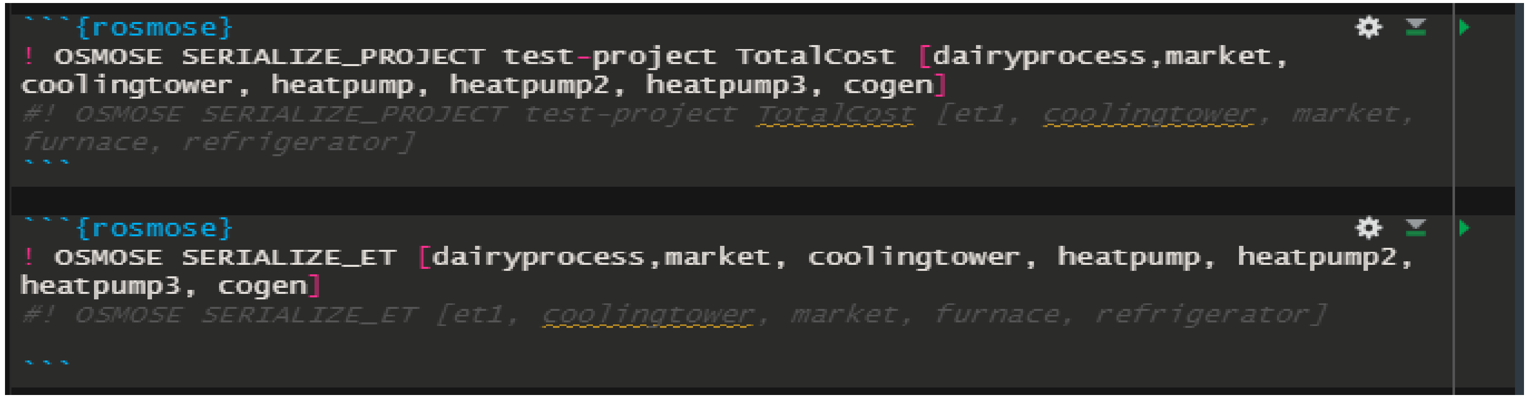
Maintain the flexibility

Open-source code



~~~
```{rosmose}
Cool_Tin = 15 [C] #Cooling tower inlet temperature
Cool_Tout = 30 [C] #Cooling tower outlet temperature
Cool_Qmax = 1000 [kW] #Cooling tower reference heat load
Cool_Elec = 0.021 [kW/kW] #Cooling Tower electricity input kWel/kWth
dtmin_liq = 5 [C] #delta Tmin of the cooling water (w/ liquid streams)
deltaH = 62.8 [kJ/kg] #Enthalpy change for cooling water @1 bar between 15 to 30°C
Twetbulb = 12.17 [C]
n = 40.0 [yr] #lifetime of a cooling tower
i = 0.06 [-] #interest rate
CEPCI_2020 = 596.2 [-] # actual CEPCI
CEPCI_2008 = 575.4 [-] # CEPCI 2008
~~~
```

Defined tags, such as operating parameters, economic indicators, physical constraints, etc.

```
```{rosmose}
E_ref_CT = %Cool_Elec%*%Cool_Qmax% [kW] # Electricity consumption
deltaT_CT = %Cool_Tout%-%Cool_Tin% [C]
approach = %Cool_Tin%-%Twetbulb% [C]
water_flow = %Cool_Qmax%/%deltaH%*3600 [kg/h] #water flow rate
watermu_CT = 0.000851*%water_flow%*(%Cool_Tout%-%Cool_Tin%) [kg/h] #makeup water in
the CT system
Annuity = (%i%*(1+%i%)**%n%)/((1+%i%)**%n%-1) [-] #annualization factor
CTCost = 746.49/0.066*((%water_flow%/1000)**0.79)*(%deltaT_CT%**0.57)*(%approach%**-0.
9924)*(0.022*%Twetbulb%+0.39)**2.447 [Euro]
Cinv2_CT = %CTCost%*(%CEPCI_2020%/%CEPCI_2008%)*%Annuity% [Euro/y]
```
```

Calculated tags (note the %_% symbols for enclosing previously defined values)

Heat streams



```
*Heat Streams*

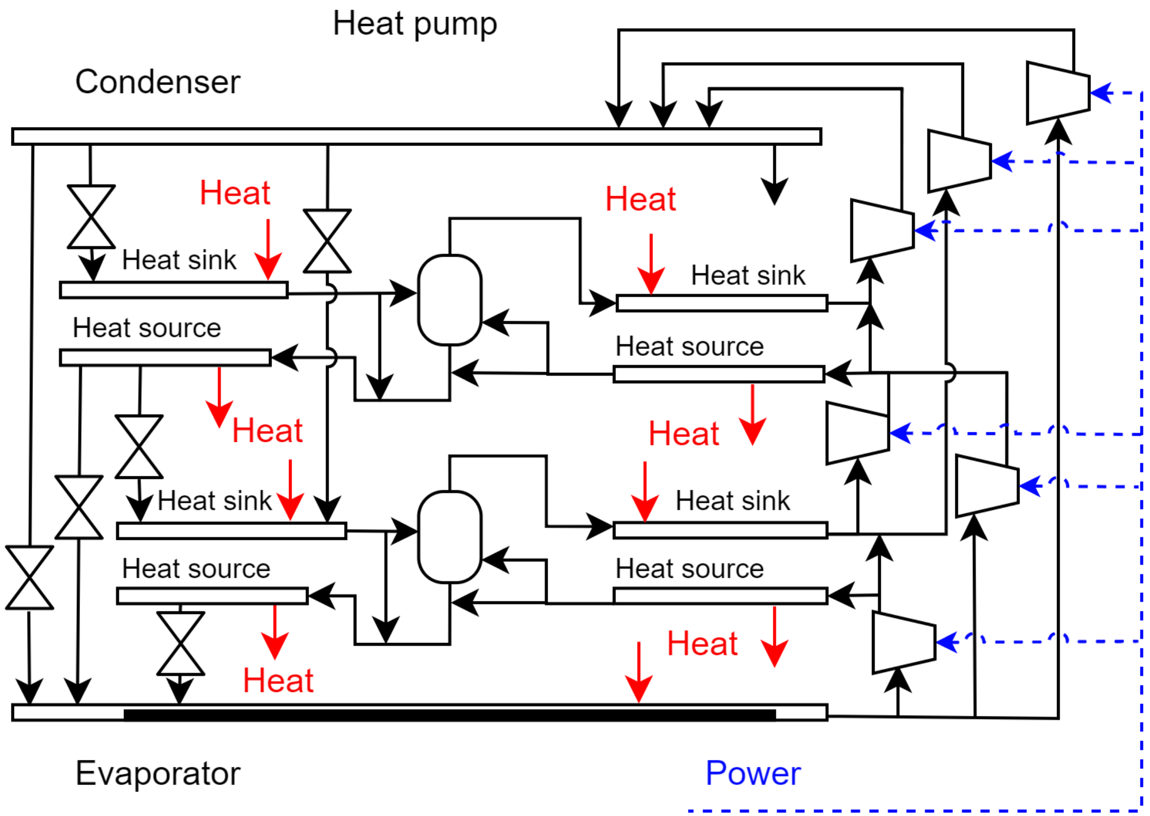
```{rosmose CoolTower_hs}
: OSMOSE HEAT_STREAMS CoolTower

|name           |Tin        |Tout       |Hin |Hout          |DT min/2       |alpha  |
|:--------------|:----------|:----------|:---|:-------------|:--------------|:------|
|cooltowerheat  |%Cool_Tin% |%Cool_Tout%| 0  | %Cool_Qmax%  | %dtmin_liq%   |1      |
```
```



```
*Resource Streams*

```{rosmose CoolTower_rs}
: OSMOSE RESOURCE_STREAMS CoolTower

|layer      |direction|value                 |
|:----------|:--------|:---------------------|
|ELEC       |in       |%E_ref_CT%            |
|WATER      |in       |%watermu_CT%          |
```
```

Resource streams



```
```{rosmose}
! OSMOSE SERIALIZE_PROJECT test-project TotalCost [dairyprocess,market,
coolingtower, heatpump, heatpump2, heatpump3, cogen]
#! OSMOSE SERIALIZE_PROJECT test-project TotalCost [et1, coolingtower, market,
furnace, refrigerator]
```
```

```
```{rosmose}
! OSMOSE SERIALIZE_ET [dairyprocess,market, coolingtower, heatpump, heatpump2,
heatpump3, cogen]
#! OSMOSE SERIALIZE_ET [et1, coolingtower, market, furnace, refrigerator]

```
```

Debugging files
```

# HP superstructure approach



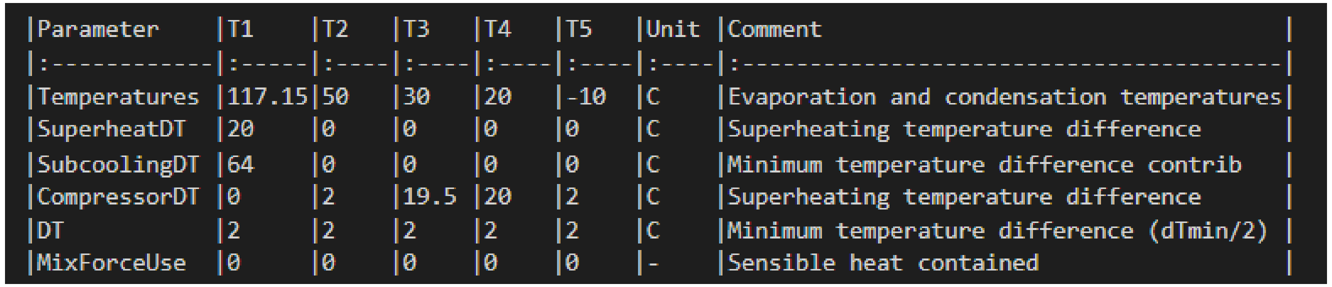
**Some fluids:**

IsoButane
Methane
Ethylene
R141b
Water
Ammonia
R123
R12
R134a
n-Propane
R1234yf
Propylene
R32
Ethane
CarbonDioxide
R13
+
Vendors data

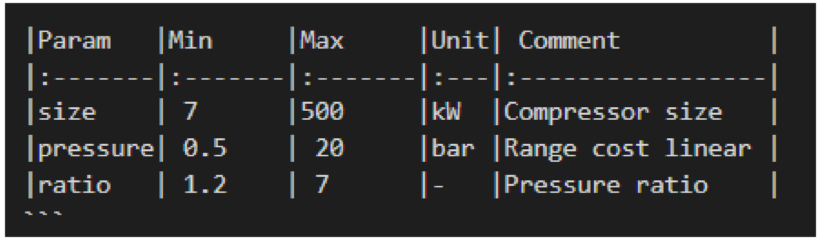
The heat pump superstructure considers a combination of evaporators, condensers, mixers, economizers, saturators, superheaters, subcoolers, and throttling valves, as well as optimal working fluids and operating conditions (e.g. temperatures, # stages, discharge T, compressor type, etc.)

# HP superstructure template

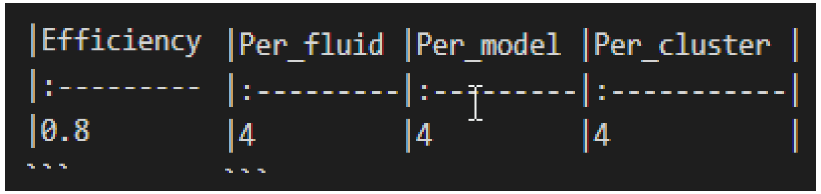
- List of candidate fluids
- Candidate temperature levels of condensers or evaporators
- Superheating and subcooling temperatures
- Minimum temperature difference contribution
- Fixed and variable investment of compressor, evaporator, and condenser
- Bounds for compressor capacity, evaporators and condensers duty
- Number of compressors per fluid
- Compressor isentropic efficiency
- Bounds of compressor pressure and pressure ratio
- Heat transfer coefficients
- Bounds of valves differential pressure
- Bounds of flash drums, mixers, and super heater (if any)
- Compressor power supply (connection layer)



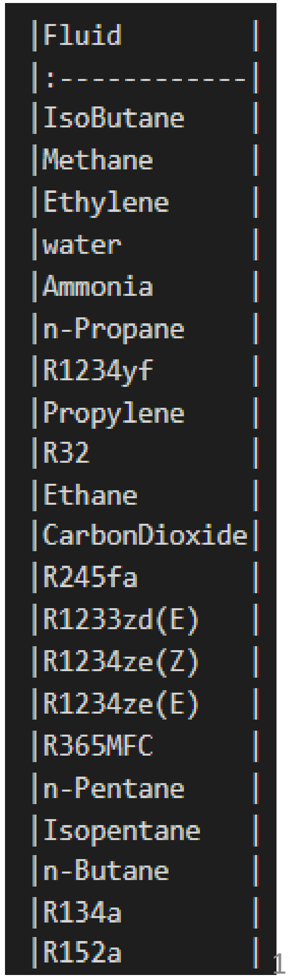
~~~~
|Parameter   |T1    |T2   |T3   |T4   |T5   |Unit |Comment                                  |
|:-----------|:-----|:----|:----|:----|:----|:----|:----------------------------------------|
|Temperatures |117.15|50   |30   |20   |-10  |C    |Evaporation and condensation temperatures|
|SuperheatDT  |20    |0    |0    |0    |0    |C    |Superheating temperature difference      |
|SubcoolingDT |64    |0    |0    |0    |0    |C    |Minimum temperature difference contrib   |
|CompressorDT |0     |2    |19.5 |20   |2    |C    |Superheating temperature difference      |
|DT           |2     |2    |2    |2    |2    |C    |Minimum temperature difference (dTmin/2) |
|MixForceUse  |0     |0    |0    |0    |0    |-    |Sensible heat contained                  |
~~~~



~~~~
|Param   |Min     |Max     |Unit| Comment          |
|:-------|:-------|:-------|:---|:-----------------|
|size    | 7      |500     |kW  |Compressor size   |
|pressure| 0.5    | 20     |bar |Range cost linear |
|ratio   | 1.2    | 7      |-   |Pressure ratio    |
```
~~~~



~~~~
|Efficiency  |Per_fluid |Per_model |Per_cluster |
|:---------  |:---------|:---------|:-----------|
|0.8         |4         |4         |4           |
```          ```
~~~~



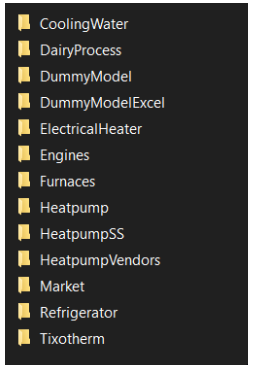
~~~~
|Fluid        |
|:-----------|
|IsoButane    |
|Methane      |
|Ethylene     |
|water        |
|Ammonia      |
|n-Propane    |
|R1234yf      |
|Propylene    |
|R32          |
|Ethane       |
|CarbonDioxide|
|R245fa       |
|R1233zd(E)   |
|R1234ze(Z)   |
|R1234ze(E)   |
|R365MFC      |
|n-Pentane    |
|Isopentane   |
|n-Butane     |
|R134a        |
|R152a        |
~~~~

Energy Technology database

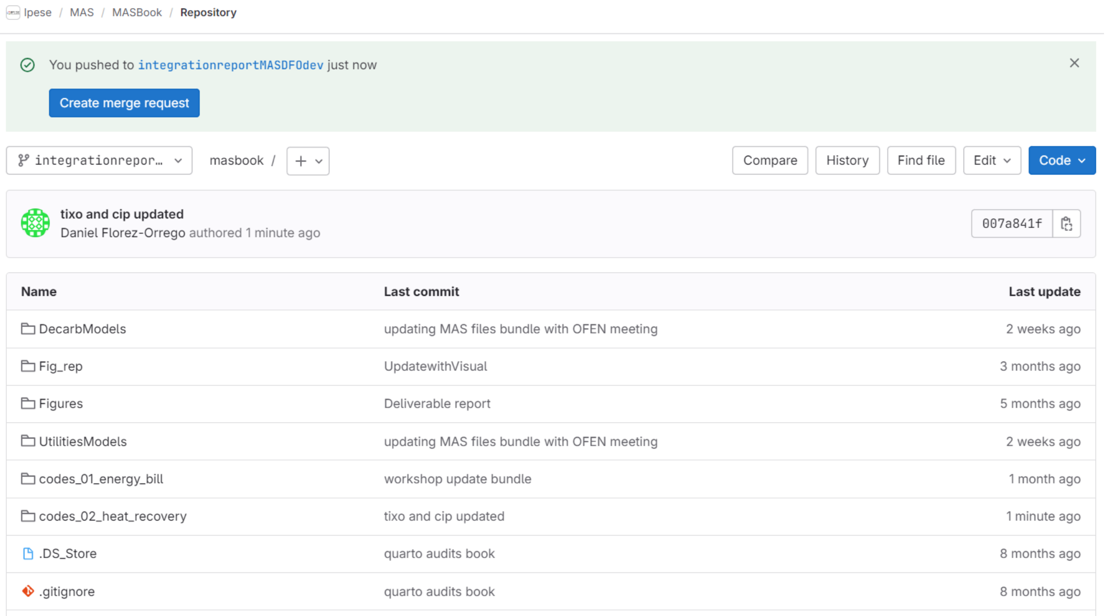
- Database technologies

Gitlab repo:

https://gitlab.epfl.ch/ipese/mas/masbook/-/tree/integrationreport



- CoolingWater
- DairyProcess
- DummyModel
- DummyModelExcel
- ElectricalHeater
- Engines
- Furnaces
- Heatpump
- HeatpumpSS
- HeatpumpVendors
- Market
- Refrigerator
- Tixotherm

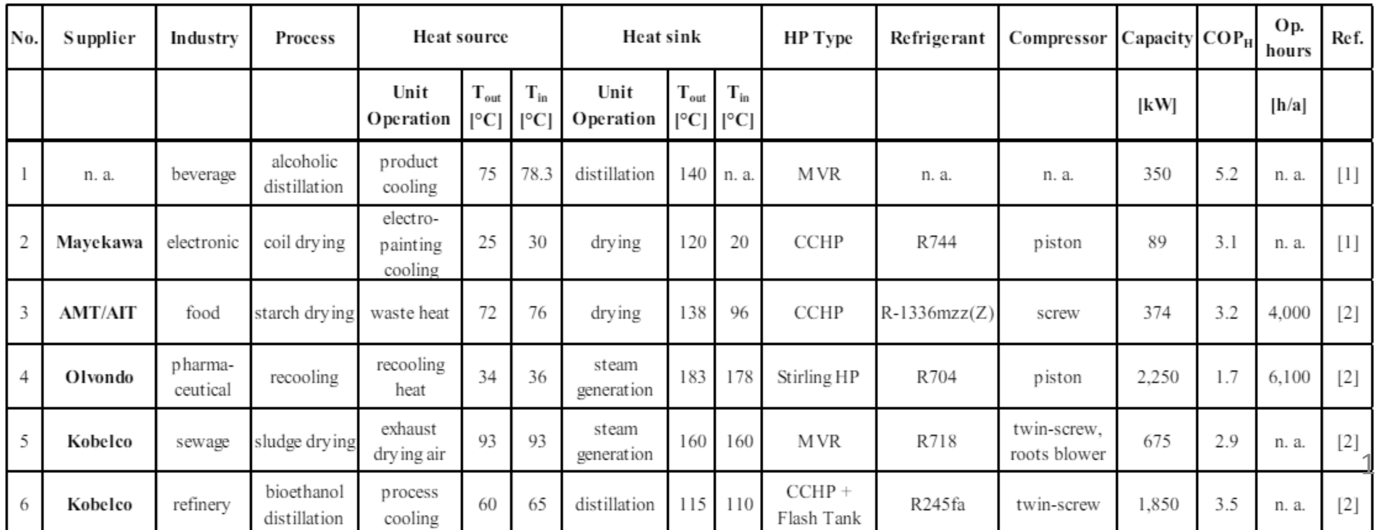


You pushed to integrationreportMASDFOdev just now

tixo and cip updated
Daniel Florez-Orrego authored 1 minute ago
007a841f

Name	Last commit	Last update
DecarbModels	updating MAS files bundle with OFEN meeting	2 weeks ago
Fig_rep	UpdatewithVisual	3 months ago
Figures	Deliverable report	5 months ago
UtilitiesModels	updating MAS files bundle with OFEN meeting	2 weeks ago
codes_01_energy_bill	workshop update bundle	1 month ago
codes_02_heat_recovery	tixo and cip updated	1 minute ago
.DS_Store	quarto audits book	8 months ago
.gitignore	quarto audits book	8 months ago

- Vendors Technologies (based on Annex 58 database)



No.	Supplier	Industry	Process	Heat source			Heat sink			HP Type	Refrigerant	Compressor	Capacity	COP_H	Op. hours	Ref.
				Unit Operation	T_{out} [°C]	T_{in} [°C]	Unit Operation	T_{out} [°C]	T_{in} [°C]				[kW]		[h/a]	
1	n. a.	beverage	alcoholic distillation	product cooling	75	78.3	distillation	140	n. a.	MVR	n. a.	n. a.	350	5.2	n. a.	[1]
2	**Mayekawa**	electronic	coil drying	electro-painting cooling	25	30	drying	120	20	CCHP	R744	piston	89	3.1	n. a.	[1]
3	**AMT/AIT**	food	starch drying	waste heat	72	76	drying	138	96	CCHP	R-1336mzz(Z)	screw	374	3.2	4,000	[2]
4	**Olvondo**	pharma-ceutical	recooling	recooling heat	34	36	steam generation	183	178	Stirling HP	R704	piston	2,250	1.7	6,100	[2]
5	**Kobelco**	sewage	sludge drying	exhaust drying air	93	93	steam generation	160	160	MVR	R718	twin-screw, roots blower	675	2.9	n. a.	[2]
6	**Kobelco**	refinery	bioethanol distillation	process cooling	60	65	distillation	115	110	CCHP + Flash Tank	R245fa	twin-screw	1,850	3.5	n. a.	[2]

- Storage systems (WIP)

Simplified GUI

- The simplified GUI is proposed to users with no coding skills:

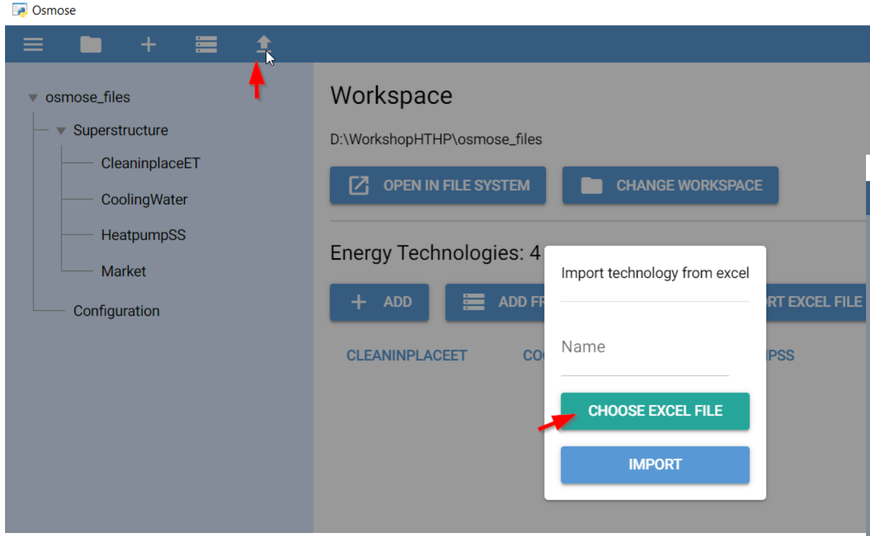
```
➢ python -m venv venv
➢ cd venv
➢ cd Scripts
➢ ./Activate.ps1
➢ pip install osmose_ui --extra-index-url=https://ipese-internal.epfl.ch/registry/pypi
➢ osmose_ui
```

Simplified GUI

Simplified GUI

Import an Excel file

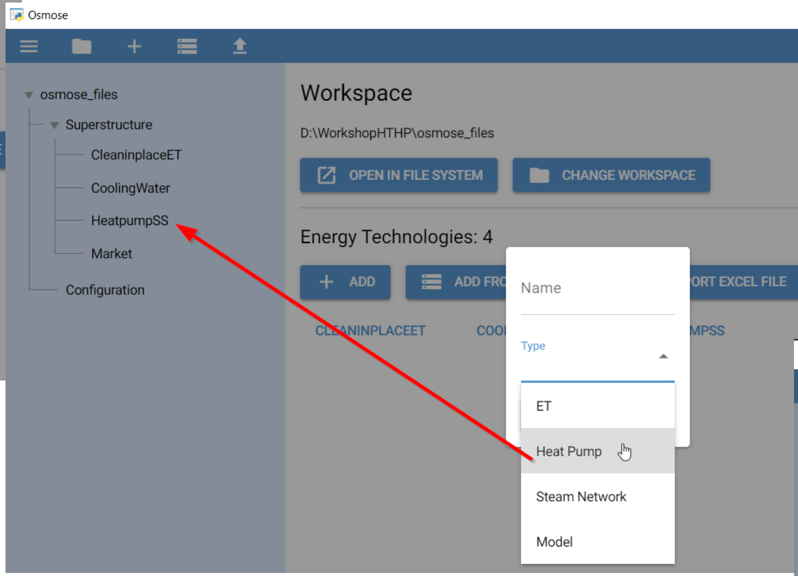
Import data to create an industrial process ET



D:\WorkshopHTHP\osmose_files

Create ETs and HP superstructures

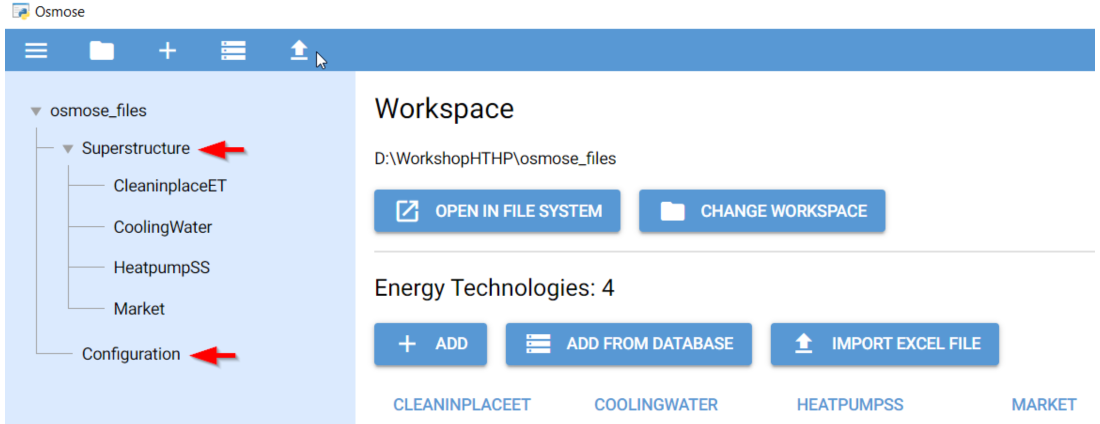
Detailed heat pump model with tunable parameters



D:\WorkshopHTHP\osmose_files

Superstructure

List of candidate utilities and an industrial process ETs



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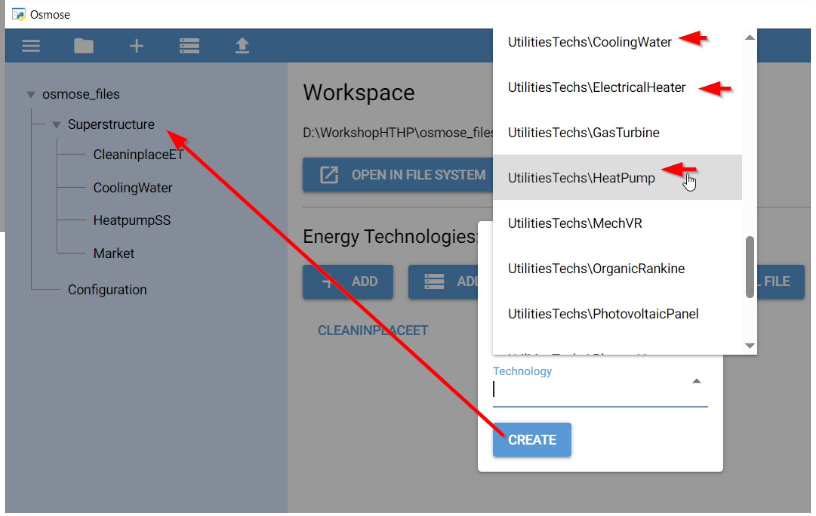

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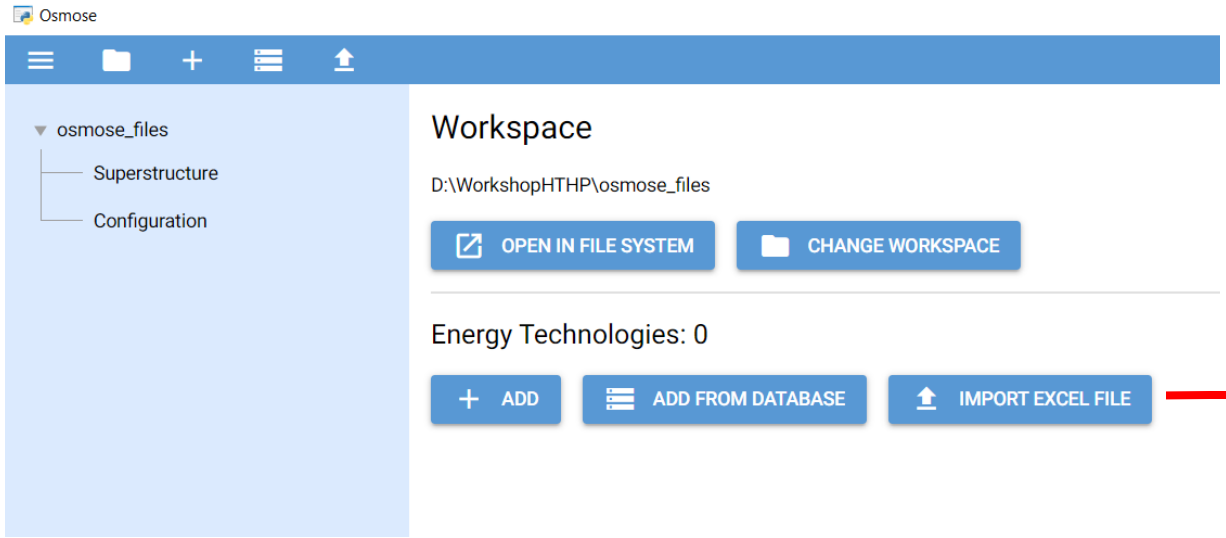
Import from ETs database

simplified HPs, competing technologies

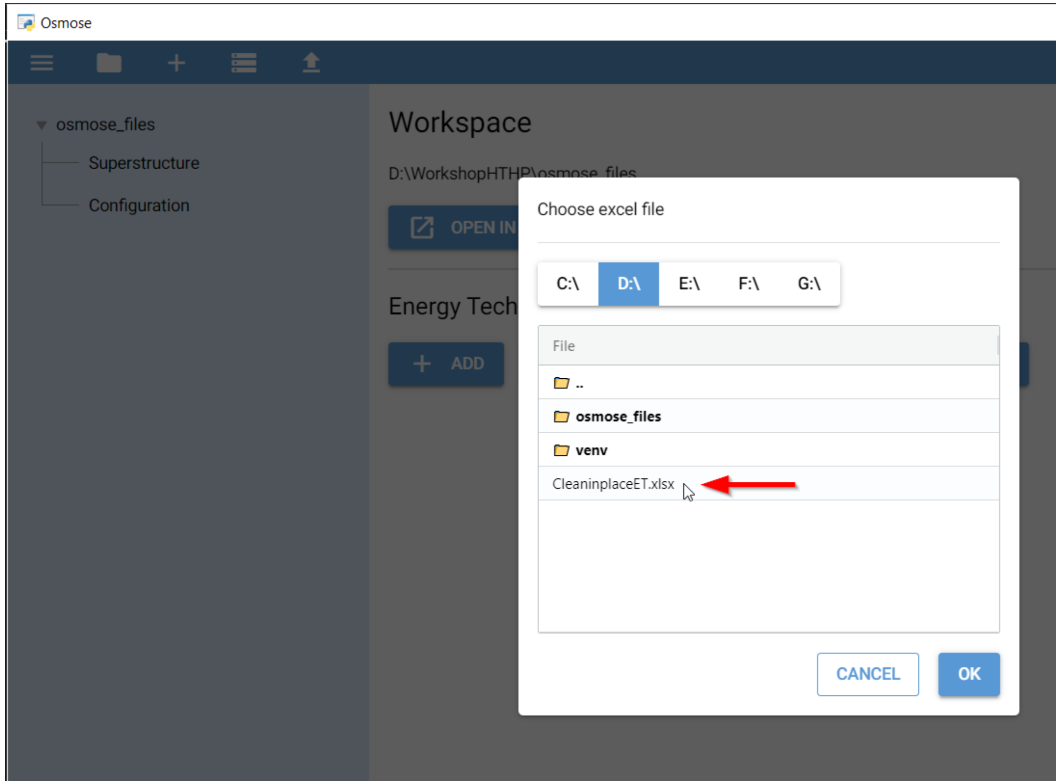
Simplified GUI



Workspace

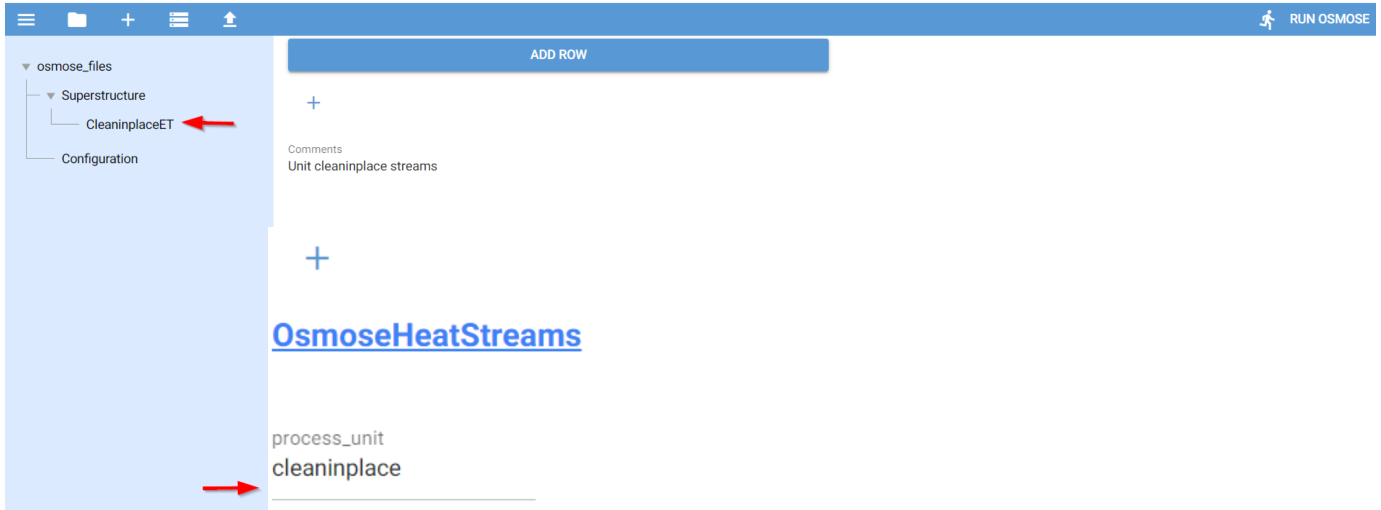
D:\WorkshopHTHP\osmose_files

Energy Technologies: 0



Choose excel file

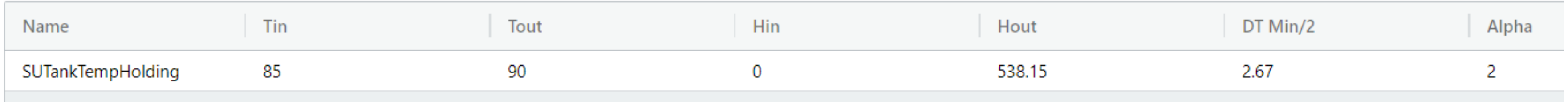
File
..
osmose_files
venv
CleaninplaceET.xlsx



Comments
Unit cleaninplace streams

OsmoseHeatStreams

process_unit
cleaninplace

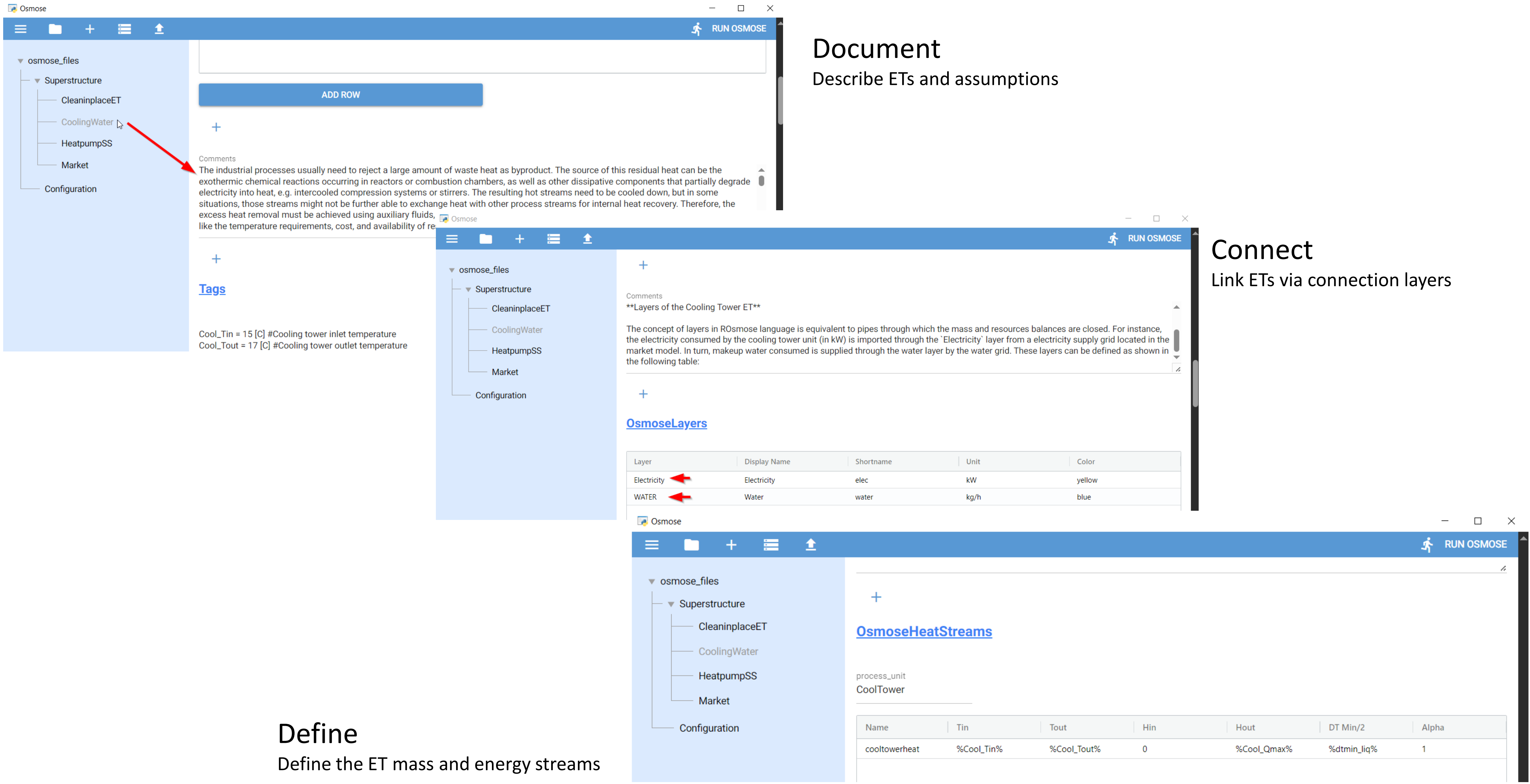


Name	Tin	Tout	Hin	Hout	DT Min/2	Alpha
SUTankTempHolding	85	90	0	538.15	2.67	2

How to import an Excel file

Import data to create an industrial process ET

Simplified GUI



Document

Describe ETs and assumptions

Comments

The industrial processes usually need to reject a large amount of waste heat as byproduct. The source of this residual heat can be the exothermic chemical reactions occurring in reactors or combustion chambers, as well as other dissipative components that partially degrade electricity into heat, e.g. intercooled compression systems or stirrers. The resulting hot streams need to be cooled down, but in some situations, those streams might not be further able to exchange heat with other process streams for internal heat recovery. Therefore, the excess heat removal must be achieved using auxiliary fluids, like the temperature requirements, cost, and availability of re

Cool_Tin = 15 [C] #Cooling tower inlet temperature
Cool_Tout = 17 [C] #Cooling tower outlet temperature

Connect

Link ETs via connection layers

Comments

Layers of the Cooling Tower ET

The concept of layers in ROsmose language is equivalent to pipes through which the mass and resources balances are closed. For instance, the electricity consumed by the cooling tower unit (in kW) is imported through the `Electricity` layer from a electricity supply grid located in the market model. In turn, makeup water consumed is supplied through the water layer by the water grid. These layers can be defined as shown in the following table:

Layer	Display Name	Shortname	Unit	Color
Electricity	Electricity	elec	kW	yellow
WATER	Water	water	kg/h	blue

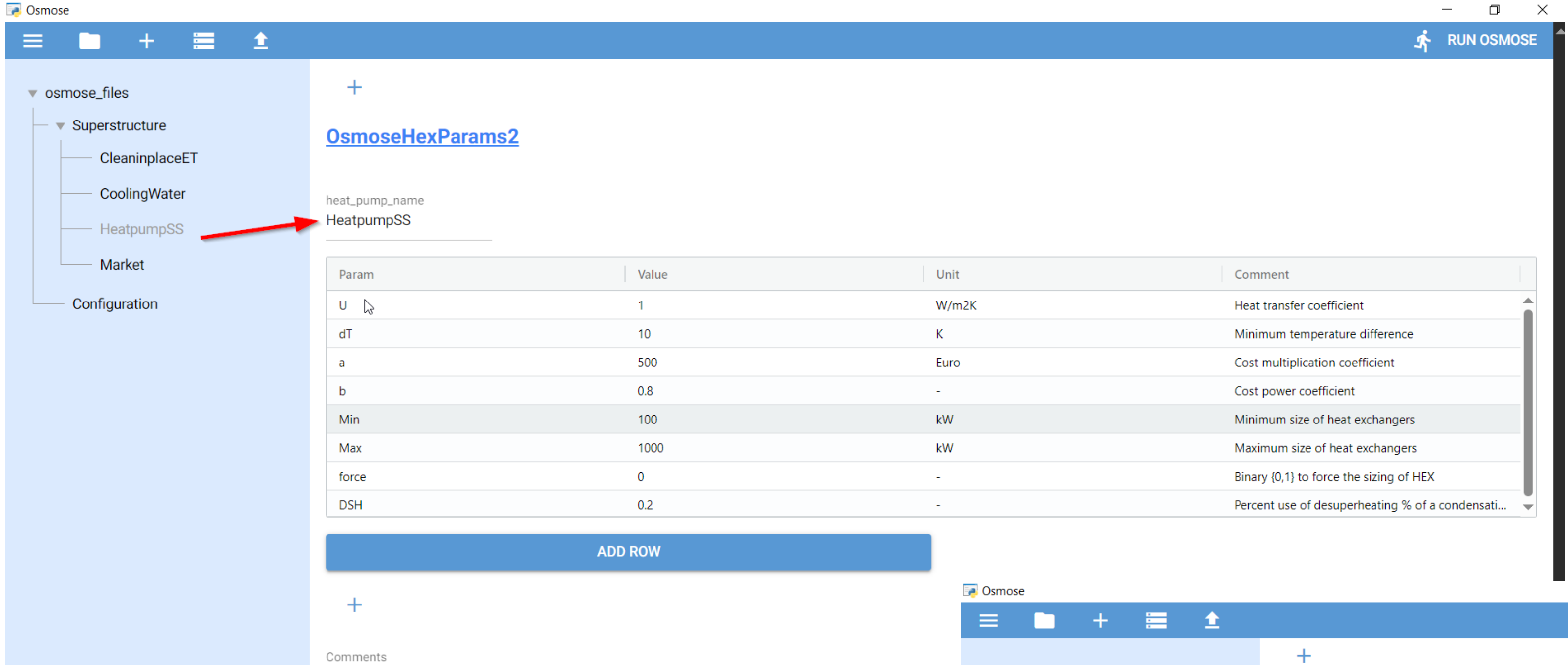
Define

Define the ET mass and energy streams

process_unit
CoolTower

Name	Tin	Tout	Hin	Hout	DT Min/2	Alpha
cooltowerheat	%Cool_Tin%	%Cool_Tout%	0	%Cool_Qmax%	%dtmin_liq%	1

Simplified GUI



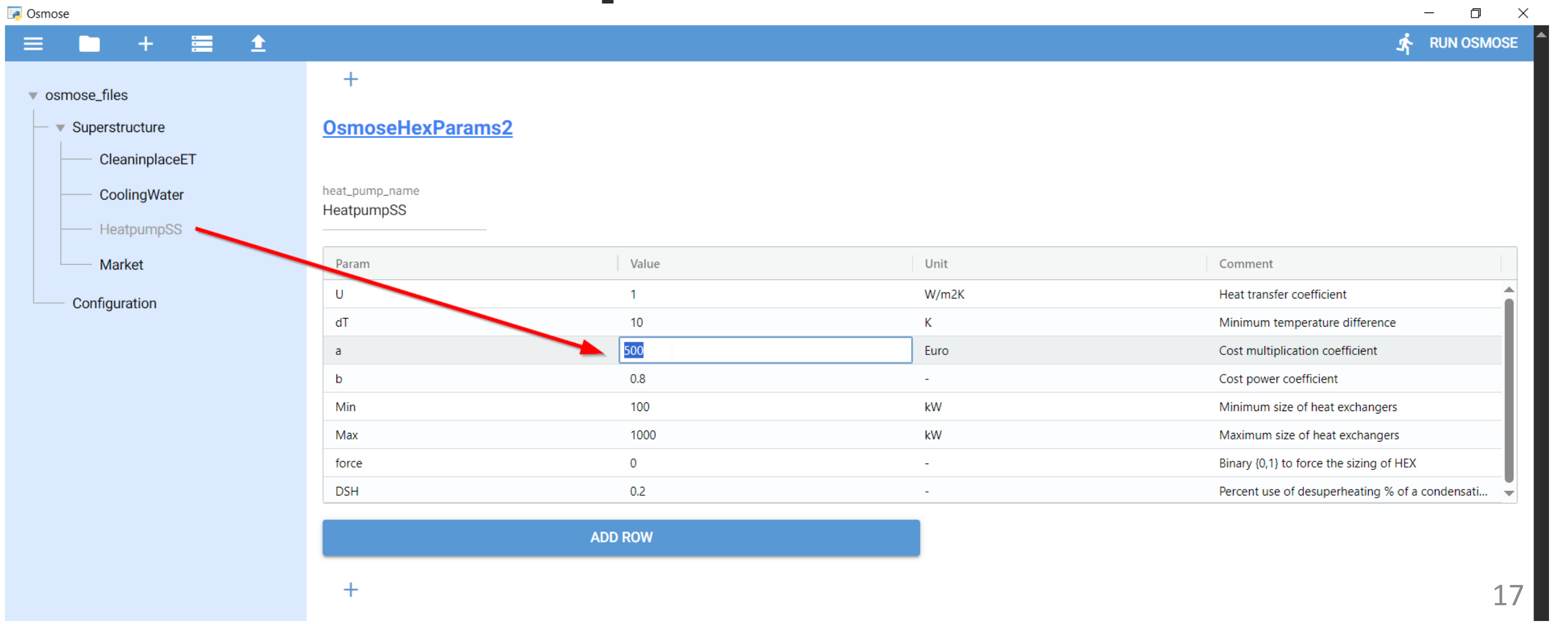
OsmoseHexParams2

heat_pump_name
HeatpumpSS

Param	Value	Unit	Comment
U	1	W/m2K	Heat transfer coefficient
dT	10	K	Minimum temperature difference
a	500	Euro	Cost multiplication coefficient
b	0.8	-	Cost power coefficient
Min	100	kW	Minimum size of heat exchangers
Max	1000	kW	Maximum size of heat exchangers
force	0	-	Binary {0,1} to force the sizing of HEX
DSH	0.2	-	Percent use of desuperheating % of a condensati...

Adapt

Fine tune parameters of HP superstructure



OsmoseHexParams2

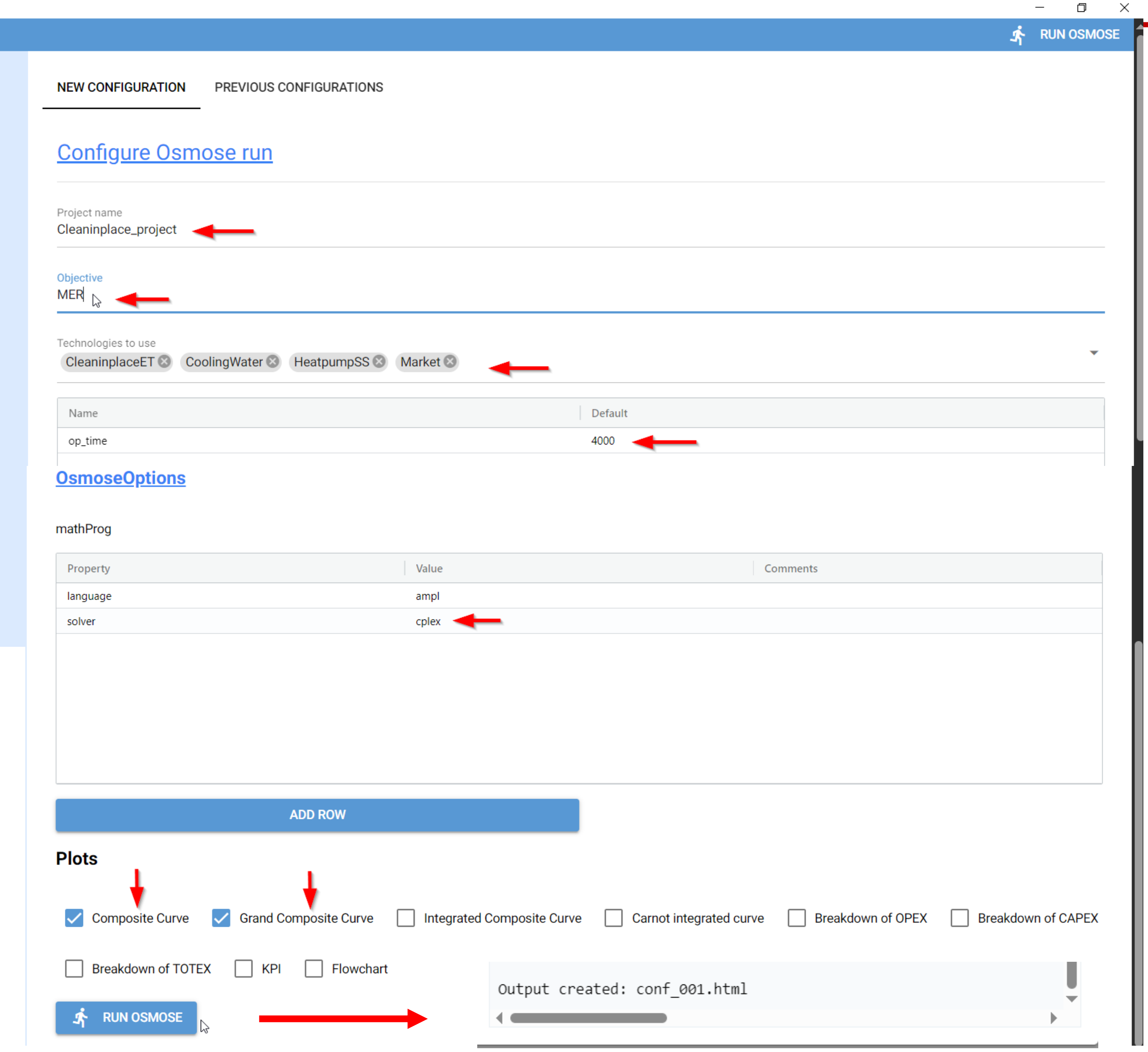
heat_pump_name
HeatpumpSS

Param	Value	Unit	Comment
U	1	W/m2K	Heat transfer coefficient
dT	10	K	Minimum temperature difference
a	500	Euro	Cost multiplication coefficient
b	0.8	-	Cost power coefficient
Min	100	kW	Minimum size of heat exchangers
Max	1000	kW	Maximum size of heat exchangers
force	0	-	Binary {0,1} to force the sizing of HEX
DSH	0.2	-	Percent use of desuperheating % of a condensati...

Edit

Edit the parameters on the simplified GUI

Simplified GUI



Configure Osmose run

Project name: Cleaninplace_project

Objective: MER

Technologies to use: CleaninplaceET, CoolingWater, HeatpumpSS, Market

Name	Default
op_time	4000

OsmoseOptions

mathProg

Property	Value	Comments
language	ampl	
solver	cplex	

Plots

☑ Composite Curve ☑ Grand Composite Curve ☐ Integrated Composite Curve ☐ Carnot integrated curve ☐ Breakdown of OPEX ☐ Breakdown of CAPEX

☐ Breakdown of TOTEX ☐ KPI ☐ Flowchart

```
Output created: conf_001.html
```

Configure

Define project name, objective function, operating hours

Set

Choose the desired optimization solver

Include

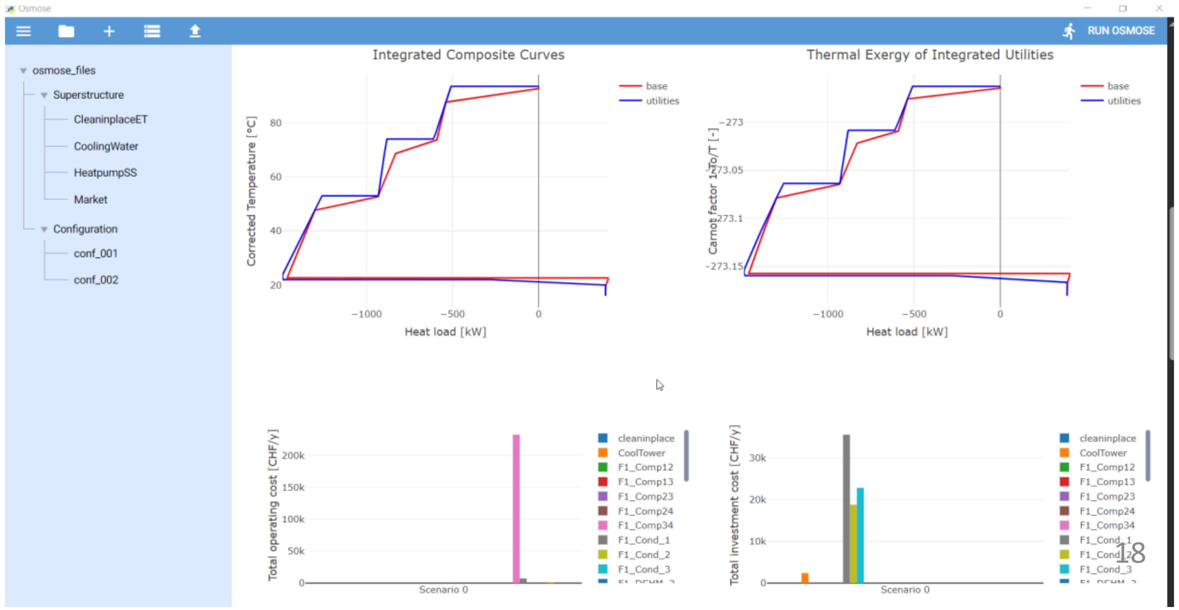
Select the KPIs to include

Execute

Run ROSMOSE tool (it may take some time to converge)

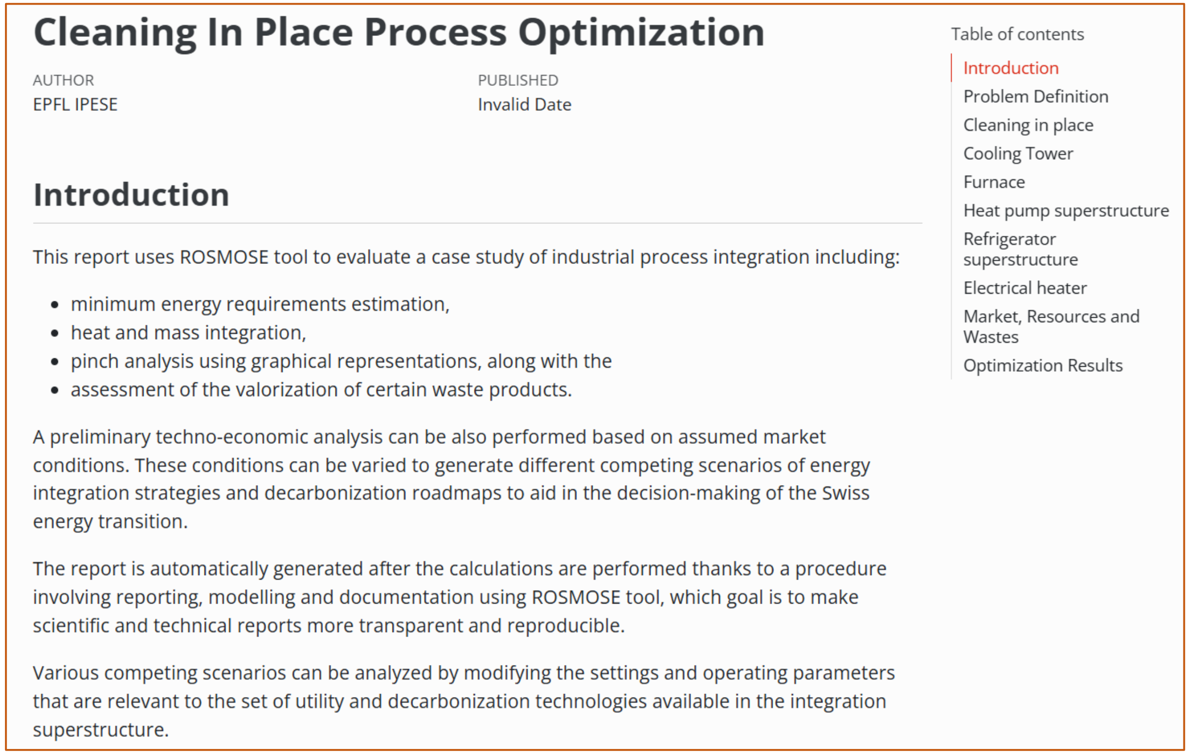
Compare

Navigate through configurations run and compare



Reporting and visualization

- HTML-based reporting format



Cleaning In Place Process Optimization

AUTHOR
EPFL IPESE

PUBLISHED
Invalid Date

Introduction

This report uses ROSMOSE tool to evaluate a case study of industrial process integration including:

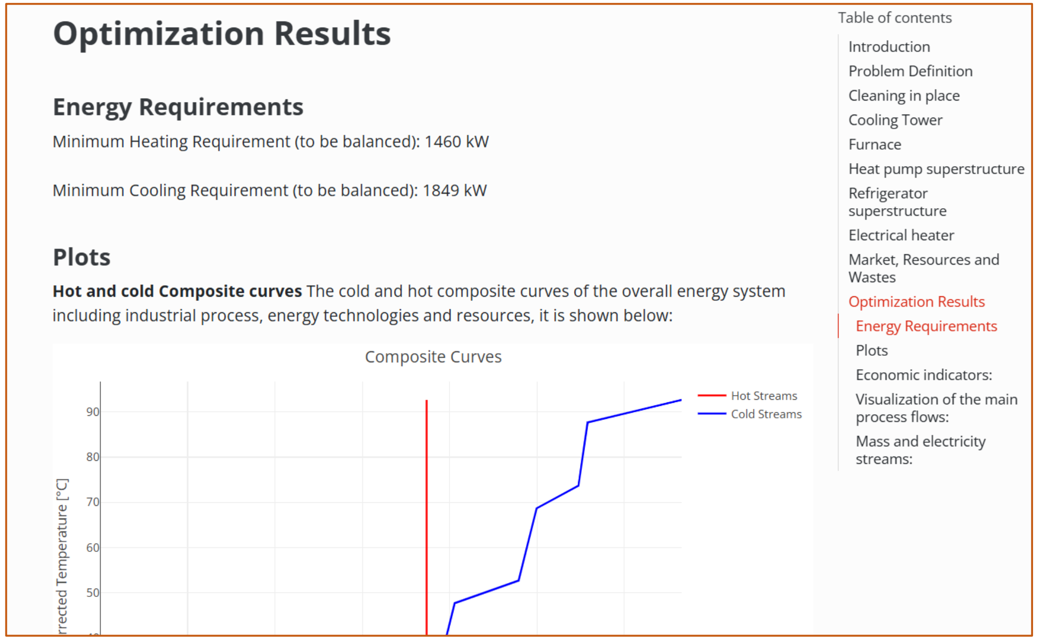
- minimum energy requirements estimation,
- heat and mass integration,
- pinch analysis using graphical representations, along with the
- assessment of the valorization of certain waste products.

A preliminary techno-economic analysis can be also performed based on assumed market conditions. These conditions can be varied to generate different competing scenarios of energy integration strategies and decarbonization roadmaps to aid in the decision-making of the Swiss energy transition.

The report is automatically generated after the calculations are performed thanks to a procedure involving reporting, modelling and documentation using ROSMOSE tool, which goal is to make scientific and technical reports more transparent and reproducible.

Various competing scenarios can be analyzed by modifying the settings and operating parameters that are relevant to the set of utility and decarbonization technologies available in the integration superstructure.

Table of contents



Optimization Results

Energy Requirements

Minimum Heating Requirement (to be balanced): 1460 kW

Minimum Cooling Requirement (to be balanced): 1849 kW

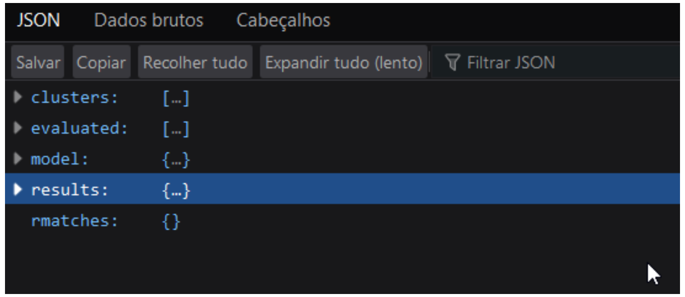
Plots

Hot and cold Composite curves The cold and hot composite curves of the overall energy system including industrial process, energy technologies and resources, it is shown below:

Table of contents

- Database of inputs and results in JSON* format

*JavaScript Object Notation



```
▸ clusters:    […]
▸ evaluated:   […]
▸ model:       {…}
▸ results:     {…}
  rmatches:    {}
```

MER

TOTEX

Typical results

The tool processes the input data for calculating:

- Minimum energy requirements (MER) (heating and cooling),
- Pinch point temperature(s),
- Graphical representations of the hot and cold composite curves (CC),
- Graphical representations of the grand composite curve (GCC),
- Graphical representations of the Carnot composite curve (CCC),
- Levels of temperature for suitable condensers and evaporators & fluids selection for HP systems,
- Compression power and coefficient of performance (COP) of HP systems,
- Mass and energy flows of the analyzed process (energy imports and exports, CO_2 emissions),
- Estimated total costing (capex + opex)
- Tailored KPIs (using FlexiCode approach)

Examples of use

Quantify waste heat recovery potential using HTHPs to reduce gas-fired boilers for heat supply:

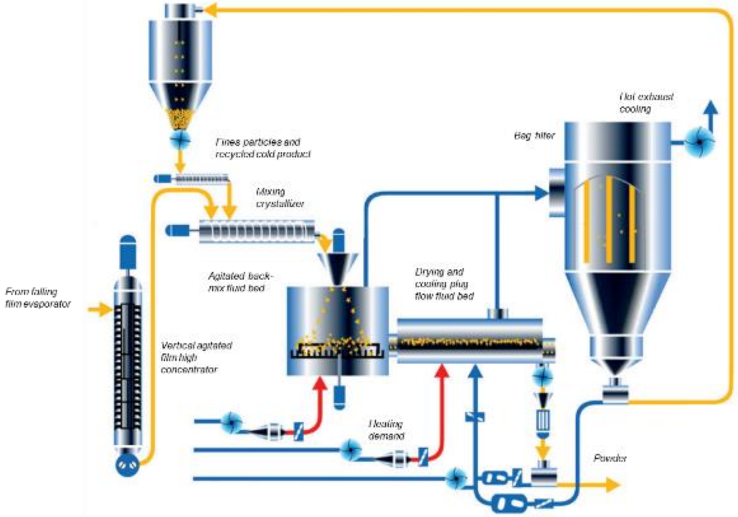
- Whey drying
- Cleaning in place

Assumptions can be modified to yield sensitivity analyses:

Parameter	Value
Electricity cost	0.2 EUR/kWh
Natural gas cost	0.07 EUR/kWh
CO_2 tax	100 EUR/tCO_2
Yearly operating hours	4000 h/y
Annualizatio factor	0.08
LHV of boiler fuel	50 MJ/kg
CO_2 emissions to fuel ratio	2.75 kg_{CO2}/kg_{fuel}
Indirect CO_2 emission factor electricity	62.63 g_{CO2}/kWh_{ee}
Indirect CO_2 emission factor fuel	0.0049 g_{CO2}/kJ_{ng}
Fired furnace investment	200 EUR/kW_{th}
Heat pump investment	450 EUR/kW
Water or air cooling systems	50 EUR/kW_{ee}

Examples of use

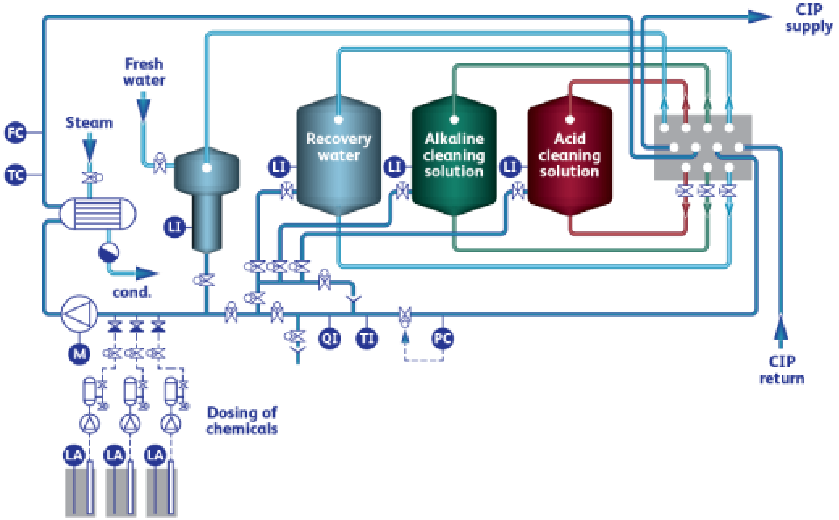
Whey and ultrafiltration retentate drying:



- does not require pre-crystallization tanks,
- high-concentration step takes place at atmospheric pressure,
- spray drying is not necessary,
- significant economic costs and energy savings (30%) can be made (Písecký 2005)

Data (anonymized) courtesy of CREMO

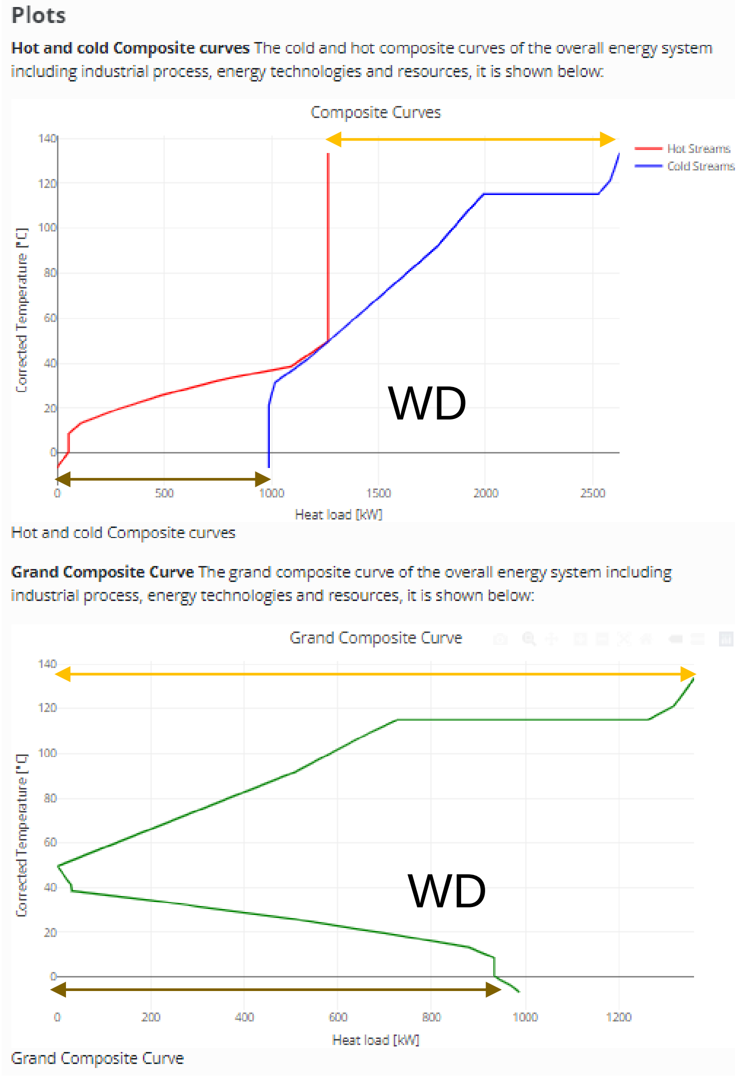
Cleaning in place system:



- keeps product quality by automated cleaning,
- eliminates products vulnerable to spoilage and bacteria growth (Solenis 2024)
- less production time lost to cleaning
- lower water and energy usage through repeatable cycle control

Data (anonymized) courtesy of ELSA

Composites and Grand Composites



Plots

Hot and cold Composite curves The cold and hot composite curves of the overall energy system including industrial process, energy technologies and resources, it is shown below:

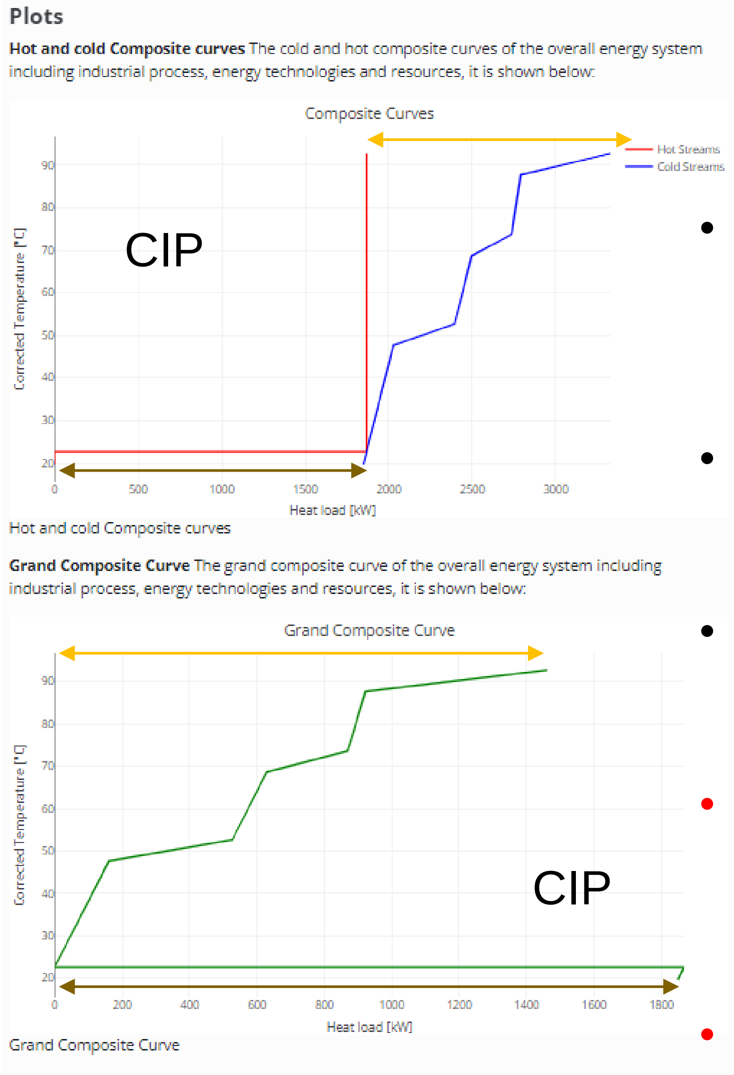
Hot and cold Composite curves

Grand Composite Curve The grand composite curve of the overall energy system including industrial process, energy technologies and resources, it is shown below:

Grand Composite Curve

Minimum Heating Requirement (to be balanced): 1362 kW

Minimum Cooling Requirement (to be balanced): 988 kW



Plots

Hot and cold Composite curves The cold and hot composite curves of the overall energy system including industrial process, energy technologies and resources, it is shown below:

Hot and cold Composite curves

Grand Composite Curve The grand composite curve of the overall energy system including industrial process, energy technologies and resources, it is shown below:

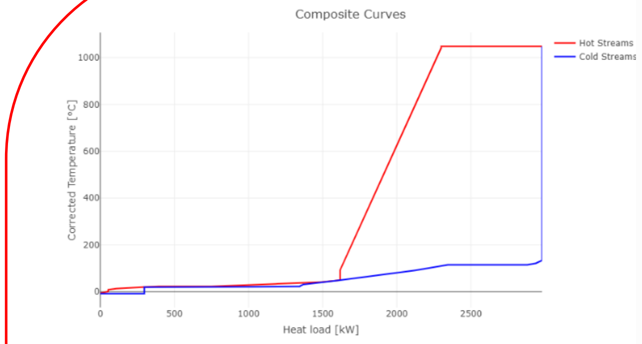
Grand Composite Curve

Minimum Heating Requirement (to be balanced): 1460 kW

Minimum Cooling Requirement (to be balanced): 1849 kW

- Availability of waste heat (1000-1800 kW) below 45 °C and 25 °C for whey drying WD and the cleaning in place CIP units, respectively.
- It could be used to feed a HTHP that upgrade waste heat up to temperatures above 90-120°C.
- Define a set of temperature levels and refrigerants that are potentially favorable.
- ROSMOSE will select the best parameters to reduce energy consumption and maximize waste heat recovery.
- Combine of multi-stage and cascaded HPs.

Results for Whey Drying



Economic indicators:

Optimized objective: obj_totalcost

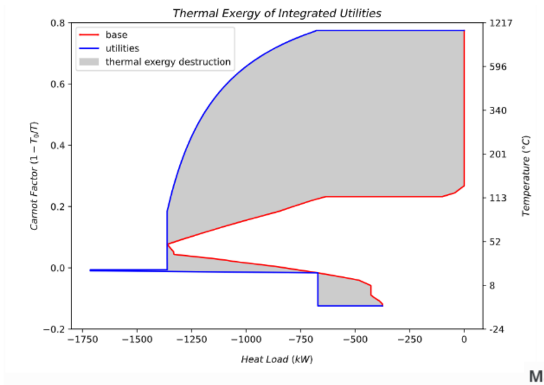
Operational expenditure (CHF/y): 600189

Capital expenditure (CHF/y): 47999

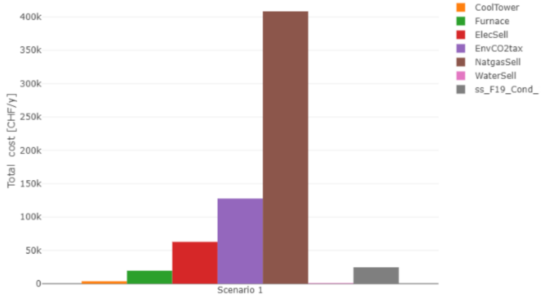
Impact (kg_{CO2}/y): 1278211

Total Expenditure (CHF/y): **648187**

Total investment (non-annualized) (CHF): 471258



Carnot integrated Curve



Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals With HP internals

Connection	From	To	Value	Units
EnvCO2Em	furnace_Furnace	market_EnvCO2tax	288.9	kg/h
EnvCO2Em	market_ElecSell	market_EnvCO2tax	4.92	kg/h
EnvCO2Em	market_NatgasSell	market_EnvCO2tax	25.74	kg/h
NATGAS	market_NatgasSell	furnace_Furnace	1459.08	kW
Electricity	market_ElecSell	coolingtower_CoolTower	21.92	kW
Electricity	market_ElecSell	refrigerator_ss_F19_Comp12	56.59	kW
WATER	market_WaterSell	coolingtower_CoolTower	101.82	kg/h

Heat pumping system details:

Total Evaporator Heat (kW): 296.7

Total Condensers Heat (kW): 353.27

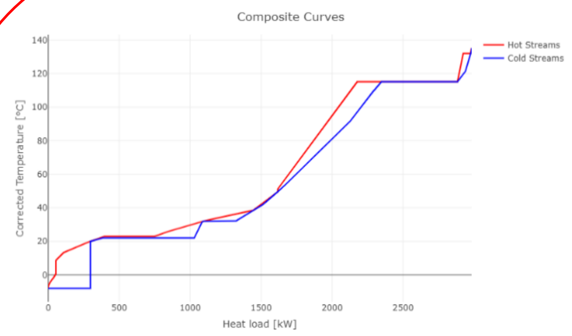
Total Compressors Power (kW): 56.59

Calculating HP overall COP (kWth/kWee): 5.24

Activated Fluids: F19

Activated Compressors: Comp12

WD Conventional Utils



Economic indicators:

Optimized objective: obj_totalcost

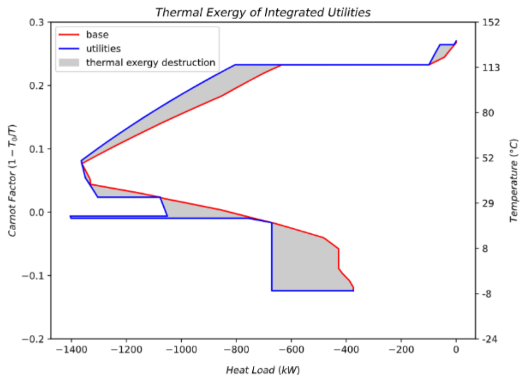
Operational expenditure (CHF/y): 381934

Capital expenditure (CHF/y): 75166

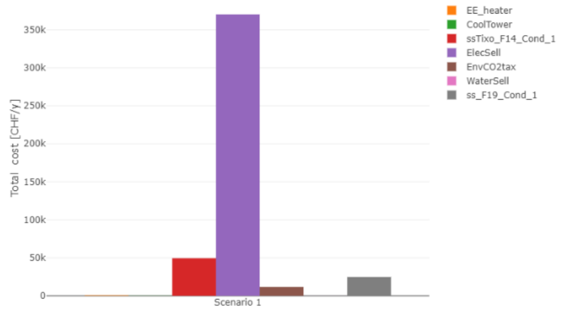
Impact (kg_{CO2}/y): 115946

Total Expenditure (CHF/y): **457099**

Total investment (non-annualized) (CHF): 737987



Carnot integrated Curve



Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Without HP Internals With HP internals

Connection	From	To	Value	Units
Electricity	market_ElecSell	refrigerator_ss_F19_Comp12	56.59	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp24	88.25	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp12	231.4	kW
Electricity	market_ElecSell	heatpump_ssTixo_F14_Comp23	30.7	kW
Electricity	market_ElecSell	coolingtower_CoolTower	1.79	kW
Electricity	market_ElecSell	HeaterEE_EE_heater	54.09	kW
EnvCO2Em	market_ElecSell	market_EnvCO2tax	28.99	kg/h
WATER	market_WaterSell	coolingtower_CoolTower	8.29	kg/h

Heat pumping system details:

Total Evaporator Heat (kW): 1243.6

Total Condensers Heat (kW): 1619.63

Total Compressors Power (kW): 406.94

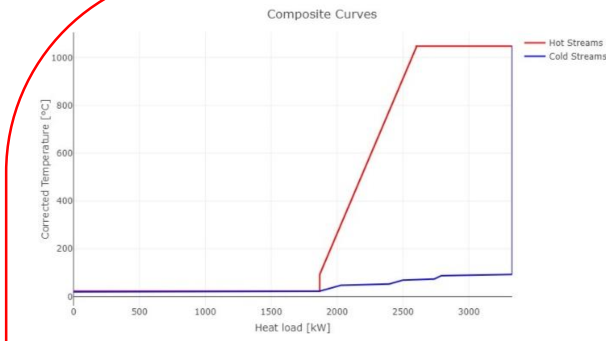
Calculating HP overall COP (kWth/kWee): 3.06

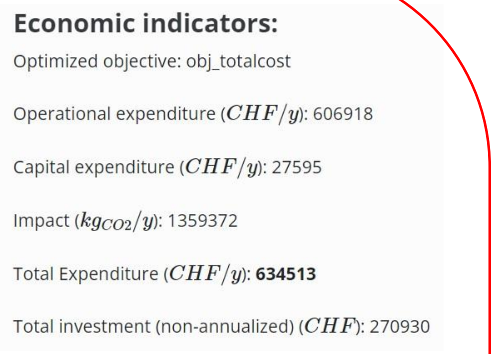
Activated Fluids: F19, F14

Activated Compressors: Comp12, Comp24, Comp23

WD HP intergation Utils

Results for Cleaning in Place





Economic indicators:

Optimized objective: obj_totalcost

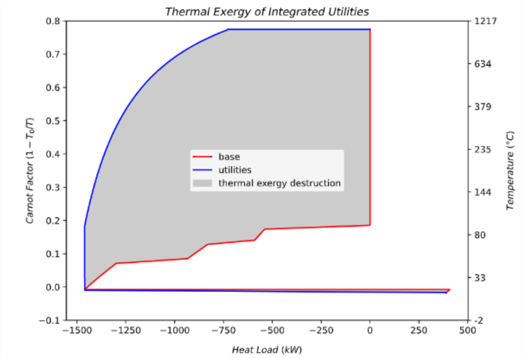
Operational expenditure (CHF/y): 606918

Capital expenditure (CHF/y): 27595

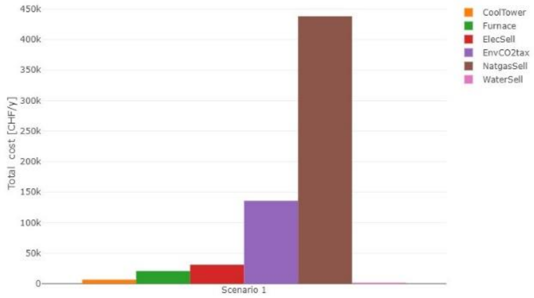
Impact (kg_{CO2}/y): 1359372

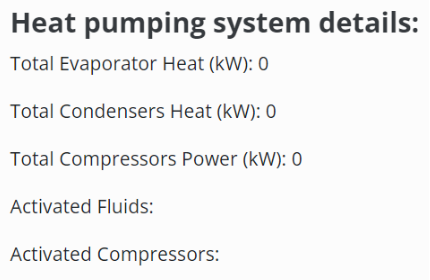
Total Expenditure (CHF/y): **634513**

Total investment (non-annualized) (CHF): 270930



Carnot integrated Curve





Heat pumping system details:

Total Evaporator Heat (kW): 0

Total Condensers Heat (kW): 0

Total Compressors Power (kW): 0

Activated Fluids:

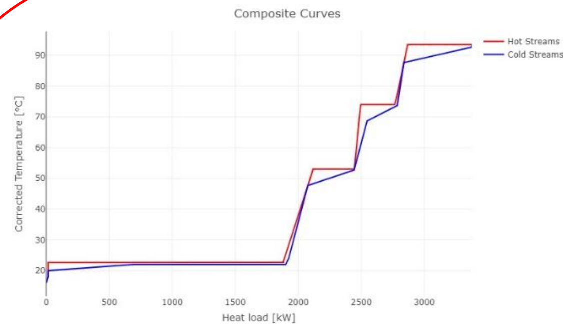
Activated Compressors:

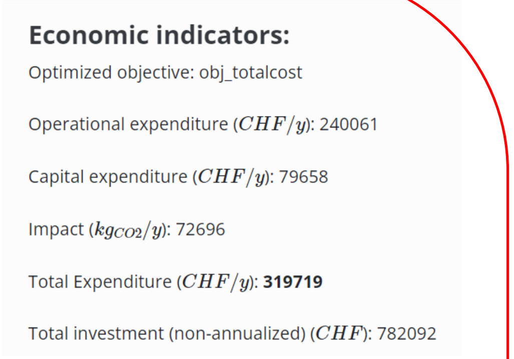
Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Connection	From	To	Value	Units
EnvCO2Em	furnace_Furnace	market_EnvCO2tax	309.81	kg/h
EnvCO2Em	market_ElecSell	market_EnvCO2tax	2.43	kg/h
EnvCO2Em	market_NatgasSell	market_EnvCO2tax	27.6	kg/h
NATGAS	market_NatgasSell	furnace_Furnace	1564.7	kW
Electricity	market_ElecSell	coolingtower_CoolTower	38.83	kW
WATER	market_WaterSell	coolingtower_CoolTower	180.39	kg/h

CIP Conventional Utils





Economic indicators:

Optimized objective: obj_totalcost

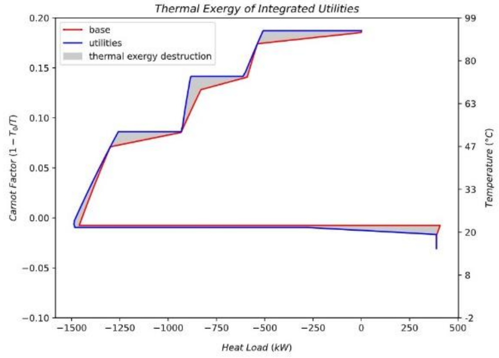
Operational expenditure (CHF/y): 240061

Capital expenditure (CHF/y): 79658

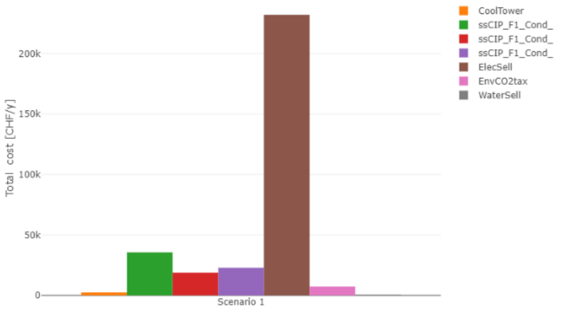
Impact (kg_{CO2}/y): 72696

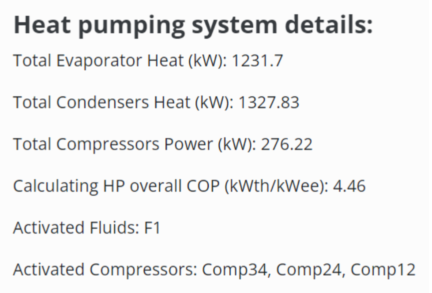
Total Expenditure (CHF/y): **319719**

Total investment (non-annualized) (CHF): 782092



Carnot integrated Curve





Heat pumping system details:

Total Evaporator Heat (kW): 1231.7

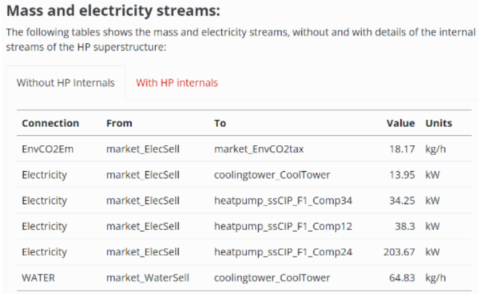
Total Condensers Heat (kW): 1327.83

Total Compressors Power (kW): 276.22

Calculating HP overall COP (kWth/kWee): 4.46

Activated Fluids: F1

Activated Compressors: Comp34, Comp24, Comp12



Mass and electricity streams:

The following tables shows the mass and electricity streams, without and with details of the internal streams of the HP superstructure:

Connection	From	To	Value	Units
EnvCO2Em	market_ElecSell	market_EnvCO2tax	18.17	kg/h
Electricity	market_ElecSell	coolingtower_CoolTower	13.95	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp34	34.25	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp12	38.3	kW
Electricity	market_ElecSell	heatpump_ssCIP_F1_Comp24	203.67	kW
WATER	market_WaterSell	coolingtower_CoolTower	64.83	kg/h

CIP HP intergation Utils

Discussion of results

- Combustion only to preheat up to 90 °C-140 °C → avoidable inefficiency.
- Conventional cases → large cooling duty.
- Untapped waste heat recovery → refrigerator condenser and water cooling reduction.
- Electrification → encourage cleaner electricity mix.

Whey drying takeaways

- Integrate two cascaded HP cycles for higher exergy efficiency. The first one works with n-butane (-10 °C → 20 °C) and the second with (R1234ze(Z)) (20 – 30°C → 117.15 °C).
- The liquid's subcooling, leaving the evaporator at the highest temperature level, can still supply a large share of the energy requirements of whey drying.
- Integrating a HTHP, the electricity consumption (462 kW) costs 370,250 EUR/y and indirect emissions achieves only 115,960 kg/y.
- It means economic savings of up to 29.5% (considering total cost), thanks to energy savings of up to 70% and emissions reduction of more than 90.9% compared to the base case scenario.

Cleaning in place takeaways

- HTHP unit features three compression stages, one evaporator (at 20 °C) and three condensers (at 95.5 °C, 76 °C and 55 °C, respectively) using R1234ze(Z) as refrigerant.
- A HTHP reduces exergy loss while almost halving the total cost (634,513 to 370,250 EUR/y) and reducing the total emissions by 95% (from 1,1359,936 kg/y to 72,680 kg/y).
- Energy savings of up to 81.9% compared to the base case scenario.
- Indirect CO_2 emissions (electricity) drop in a future scenario of decarbonization strategies based on electrification, considering that the supply chains of both energy commodities become comparable for the current electricity mix assumptions.

Conclusions and path forward

- Process electrification and waste heat valorization are crucial to defossilize heat supply in food and beverage industries ***(favorable temperature levels)***.
- Competition between different utility systems → a tool to systematically compare the performance of those alternative technologies.
- Automated computational and reporting tools → modeling, reporting and comparing energy integration scenarios.
- CO_2 tax and waste heat valorization → HP deployment by offsetting initial investments.
- Challenges related to reliability, space budget and maintainability → risk perception within firms.
- Preliminary analyses → significant waste heat recovery using HTHPs and environmentally friendly.

Path forward

- Massive deployment of the web-based tool, training programmes, and business model.
- Servers hosting and confidentiality, local installation vs. external servers.

Future developments and projects

- Installation, maintenance, and handling of confidential data in servers hosted by EPFL.
- Adopt a scalable infrastructure and address robust and secure data handling (authentication).
- Containerization (e.g., Docker) of required libraries for optimization and visualization avoiding external servers.

Projects and courses that have been and will use and further validate the tool:

- HTHP Annex 58 Swiss (IEA)
- Task XXIV IETS TCP (IEA)
- Master of Advanced Studies (EPFL/HESSO)
- Pinch Bot (SFOE)
- Advanced Energetics (Graduate course at EFPL)
- Industrial projects in IPESE (EPFL, Novelis, LDC, Buhler, Richemont, Terega, Morand, Hermes, CIMO...)

Lessons and messages

Lessons:

1) Assessing the competition between different utility systems requires a tool to systematically and objectively compare the performance of alternative technologies.

2) Automated computational and reporting tools can speed up modeling, reporting and comparison of energy integration scenarios.

3) Adopting new decision-support tools can be facilitated by integrating familiar data-handling platforms, like Excel, while still benefiting from the flexibility of open-source programming languages and libraries.

Messages:

1) Developing decision support tools that fit different users' profiles entails prioritizing intuitive, flexible and versatile open-source toolkits.

2) An inclusive and sustainable energy transition will require equipping qualified engineers with powerful tools to leverage models databases and routines for industrial diagnosis and optimization.

3) Key challenges in ensuring the sustainability and consistency of open-source tools include addressing web scalability, maintainability, server hosting, and confidentiality issues.

Acknowledgements

The team acknowledges the Swiss Federal Office of Energy (SFOE) for supporting the project:

Annex 58 HTHP-CH: Integration of High-Temperature Heat Pumps in Swiss Industrial Processes

N°.SI/502336-01

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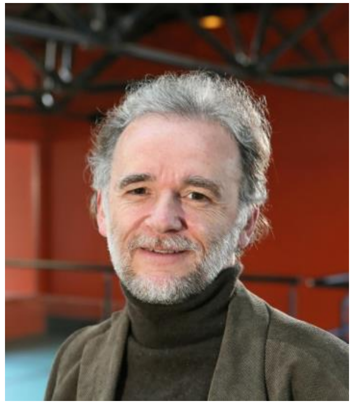

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- Soline Corre, PhD Student, Mech. Eng. (Switzerland)
- Lander Cortvriendt, MSc. Chem. Eng. (Belgium)
- Joao Ferreira da Silva, IT specialist (Portugal)
- Joseph Loustau, IT support (Switzerland)

References

Publications

- Florez-Orrego, D., et al. A systematic framework for the multi-time integration of industrial complexes and urban systems. **7th Intl Conf. CPOTE**, 20th-23th September, 2022. Warsaw, Poland.
- Florez-Orrego, D. et al. **Heat pumping** and renewable energy integration for decarbonizing brewery industry and district heating. In: **Computer Aided Chemical Engineering**. Elsevier, pp. 3177–3182. 2023
- Flórez-Orrego, D., et al. Techno-economic and environmental analysis of **high temperature heat pumps** integration into industrial processes: the ammonia plant and pulp mill cases. **Sust. Energy Technol. Assess** 2023; 60: 103560.
- Dardor, D., Florez-Orrego, D. et al. ROSMOSE: A web-based optimization tool to aid decision-making for the design and operation of industrial and urban energy systems, **Energy**, v. 304, 2024, pp132182.
- Florez-Orrego, D., Dardor, D., Ribeiro Domingos MEG, et al (2024) Continuous training program: process engineering for decarbonization of the Swiss industry. **SuisseEnergie, Swiss Federal Office of Energy**, https://infoscience.epfl.ch/handle/20.500.14299/240549
- Florez-Orrego, D., Dardor D., Ribeiro Domingos, M., et al (2024) A web-based decision support tool for the design and integration of industrial **high-temperature heat pumps**. **Wärmepumpen Tagung**, Bern, June 26th, 2024.

Other sources

- Pisecky, J. Handbook of milk powder manufacture, Second Edition. **GEA**. Copenhagen, 2012.
- Wallerand, A., et al. **Optimal heat pump integration** in industrial processes. **Applied Energy**,2018; 219: 68–92.