Integration of LCA framework into Renewable Energy Hub Optimizer (REHO)

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Renewable Energy Hub Optimizer (REHO)

REHO optimally configures energy systems to minimize the specified objective function

- ***Inputs:*** ***EUDs, the resources, the equipments***
- ***Outputs:*** ***Decision variables, KPIs***

Workflow of Utilizing REHO

Preparations for inputs according to the pilot site

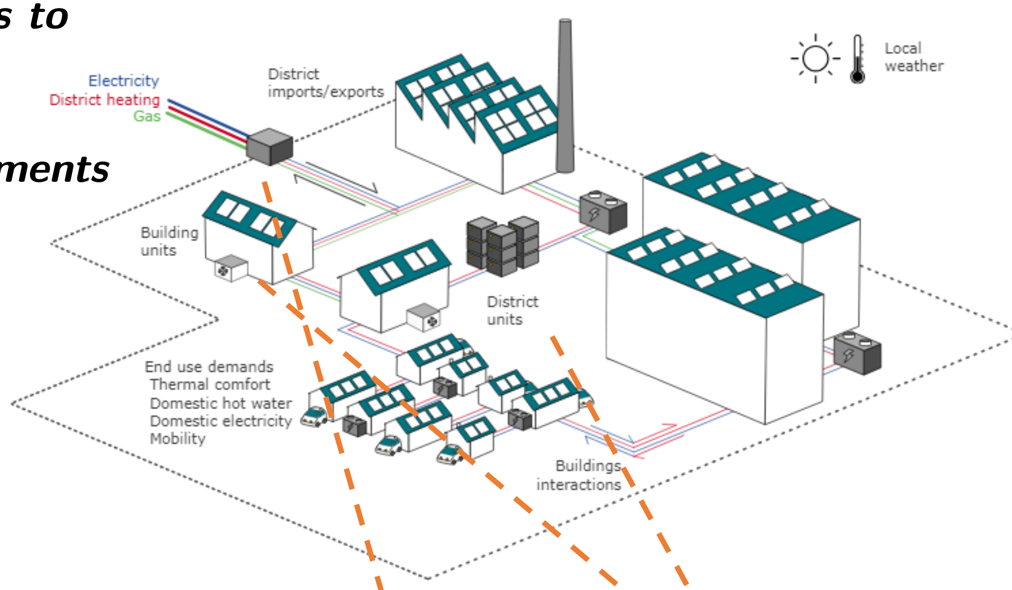
↓

Optimization executions for different scenarios

↓

Results analyzing

District-level energy hub in REHO[1]



$$LCA_{tot} = LCA_{op} + LCA_{constr}$$

An energy hub is a unit where multiple energy carries can be converted, conditioned, and stored[2].

User friendly and open source

[1] Dorsan Lepour, Cédric Terrier, and Joseph Loustau. Renewable Energy Hub Optimizer (REHO) - A Comprehensive Decision Support Tool for Sustainable Energy System Planning
[2] M Geidl, G Koeppel, P Favre-Perrod, B Klockl, G Andersson, and K Frohlich. "Energy hubs for the future". In: IEEE Power and Energy Magazine 5.1 (Jan. 2007), pp. 24–30.

Introduction

Renewable Energy Hub Optimizer (REHO)

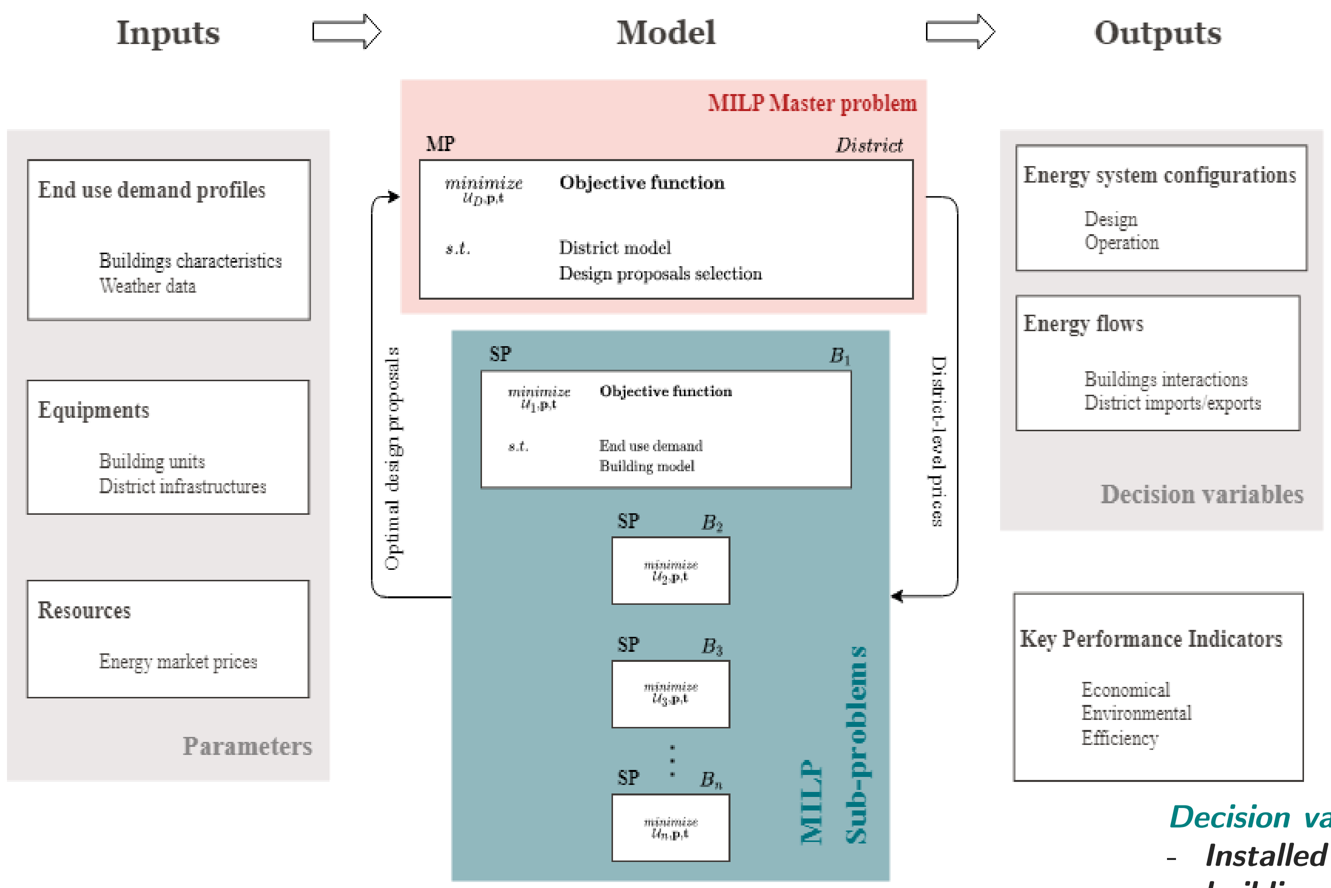
REHO model architecture[1]

Building characteristics
- *Usage type*
- *Morphology*
- *Heating performance*

Weather data
- *Outdoor ambient temperature*
- *Global irradiation*

Equipments:
energy conversion and energy storage technologies

Resources:
energy carrier it transports and its specifications



Decision variables:
- *Installed capacities for building-level and district-level units*
- *Operation time throughout a year*

[1] Dorsan Lepour, Cédric Terrier, and Joseph Loustau. Renewable Energy Hub Optimizer (REHO) - A Comprehensive Decision Support Tool for Sustainable Energy System Planning

Nevertheless, there are still several issues existing in the current REHO regarding LCA

A more comprehensive and convincing LCA database

Current REHO LCA Model →

A unified and more advanced LCA methodology

Lifecycle Assessment (LCA)

1. *Lack of units for values and absence of declared data sources in LCA database*
2. *Inadequate methodological framework.*
3. *Need for a standardized LCA methodology to enable valid comparisons*

Therefore, there is a strong need to integrate a better LCA framework into REHO.

LCA Framework Integration

LCA formula

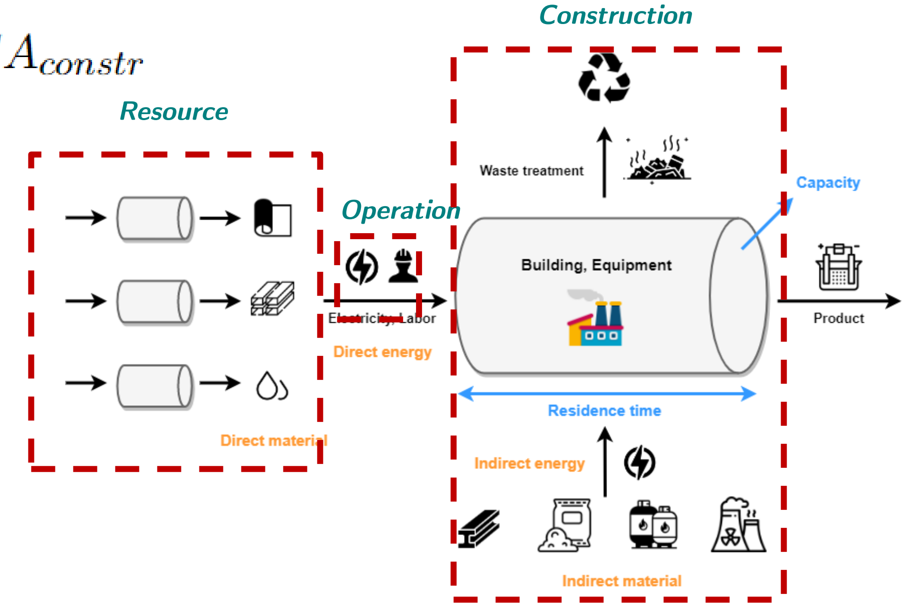
3 types of environmental impacts

$$LCA_{tot} = LCA_{op} + LCA_{constr}$$

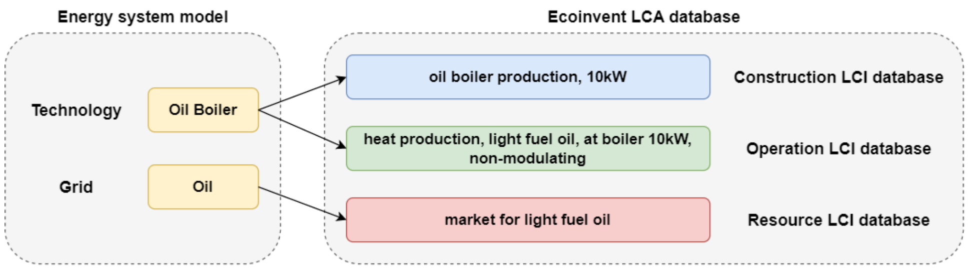
$$LCA_{tot} = LCA_{res} + LCA_{op} + LCA_{constr}$$

General Methodology for LCA

Any conversion process can be abstracted into a conduit:



In Ecoinvent, corresponding items can be found for each type of LCA process.



LCA Framework Integration

LCA resource

- ***Including the resource extraction stage allows us to capture the environmental impacts associated with the extraction of resources***

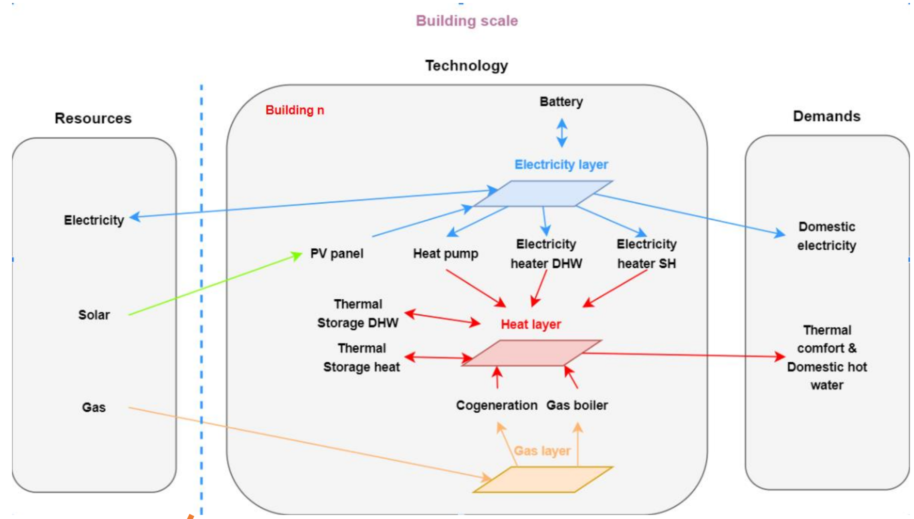
- ***The LCA is performed by calculating the difference in energy carriers between grids and districts, then multiplying by the respective unit environmental impacts from the database.***

$$EI_{sup}(l,u,t) = ei_{supply}(l,u,t) \cdot Network_{supply}(l,u,t)$$

$$EI_{dem}(l,u,t) = ei_{demand}(l,u,t) \cdot Network_{demand}(l,u,t).$$

$$LCA_{res} = \sum_{l \in ResourceBalances, u \in units, t \in Time} (EI_{sup}(l,u,t) - EI_{dem}(l,u,t))$$

Building scale example



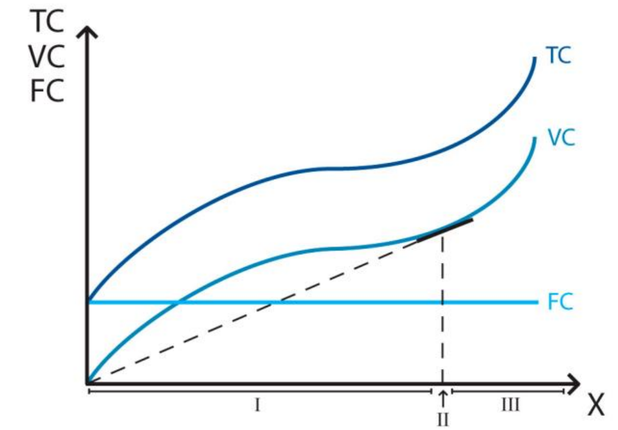
$Ei_{sup}(l,u,t)$——is the total environmental impacts retrieved of unit u supply to the energy layer l at time t

$Ei_{dem}(l,u,t)$——is the total environmental impacts generated of unit u supply to the energy layer l at time t

$Ei_{supply/demand}$——the unit environmental impacts in LCA database, in this case, Ecoinvent

LCA Database Double Counting Removal

LCA construction



Original REHO

Fixed environmental impacts — *Variable environmental impacts*

$$LCA_{constr} = \sum_{u \in Units} \frac{UseofUnits(u) * ei_{fixed}(u) + SizeofUnits(u) * ei_{variable}(u)}{lifetime(u)}$$

- ***Lack of literatures for scale up effects in LCA***
- ***Difficulty for interpretations for fixed environmental impacts***

New methodology

$$LCA_{constr} = \sum_{u \in Units} \frac{SizeofUnits(u) * ei_{variable}(u)}{lifetime(u)}$$

LCA_{constr} —— is the total environmental impacts for construction of units
$ei_{variable}$ —— is the unit variable environmental impacts extracted from Ecoinvent
SizeofUnits(u) —— the installed capacity of unit u
lifetime(u) —— the lifetime of the unit u

LCA Framework Integration

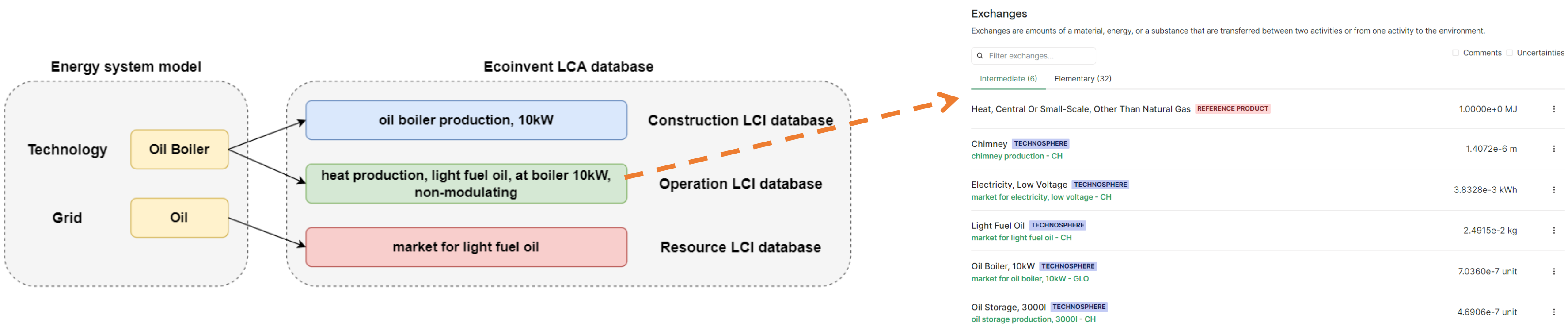
LCA operation

$$LCA_{op} = \sum_{l \in ResourceBalances, u \in Units, t \in Time} ei_{op}(u) * Units\_Supply(l,u,t)$$

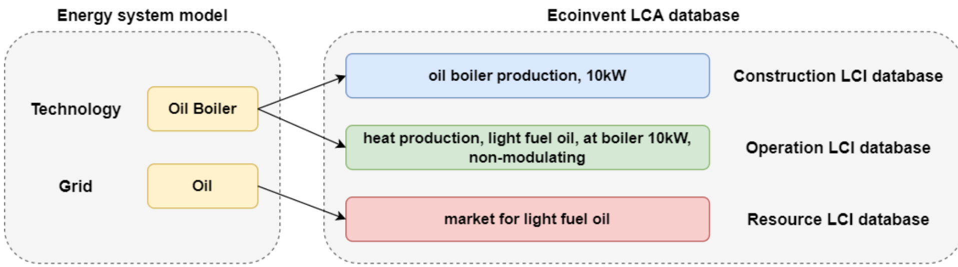
Double Counting needs to be removed!

LCA_{op} —— is the total environmental impacts for operation
Units_supply (l,u,t)——is the total unit u's production in energy layer l within the time period t

Double counting



Double counting removal



Exchanges

Exchanges are amounts of a material, energy, or a substance that are transferred between two activities or from one activity to the environment.

Filter exchanges...

Comments Uncertainties

Intermediate (6) Elementary (32)

Heat, Central Or Small-Scale, Other Than Natural Gas REFERENCE PRODUCT 1.0000e+0 MJ

Chimney TECHNOSPHERE
chimney production - CH 1.4072e-6 m

Electricity, Low Voltage TECHNOSPHERE
market for electricity, low voltage - CH 3.8328e-3 kWh

Resources

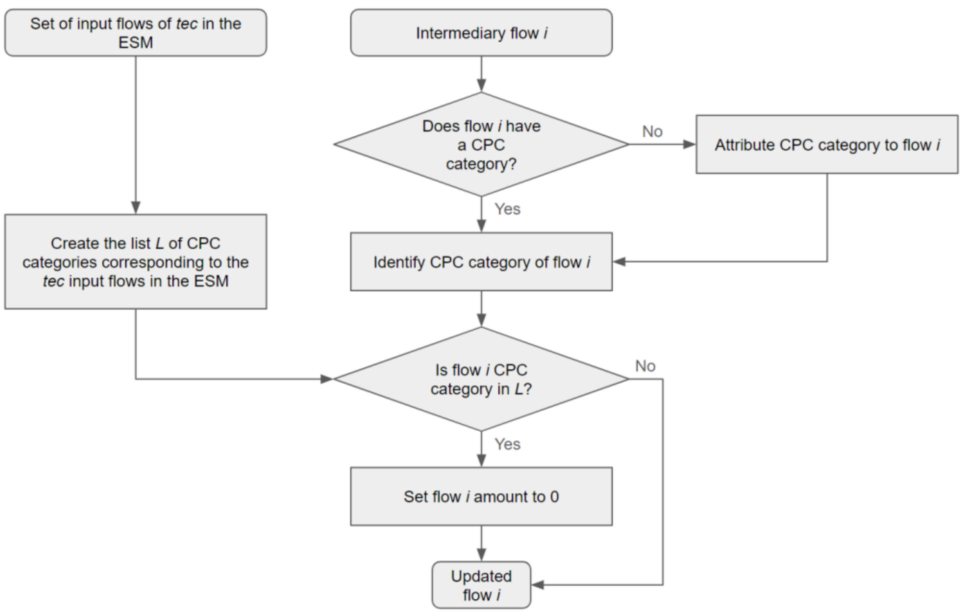
Construction

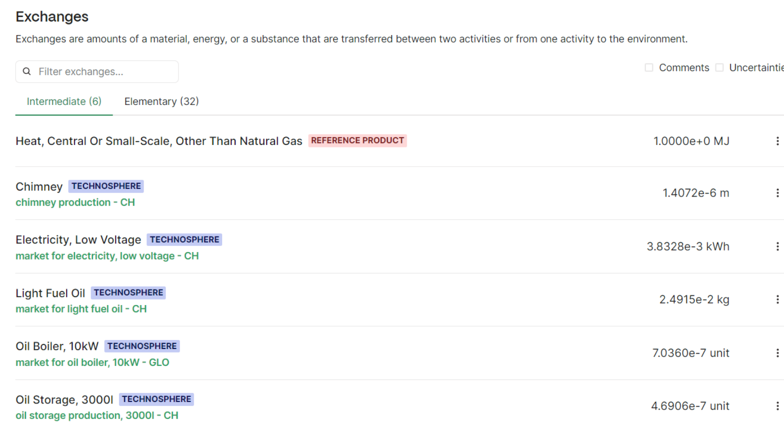
Oil Storage, 3000l TECHNOSPHERE
oil storage production, 3000l - CH 4.6906e-7 unit

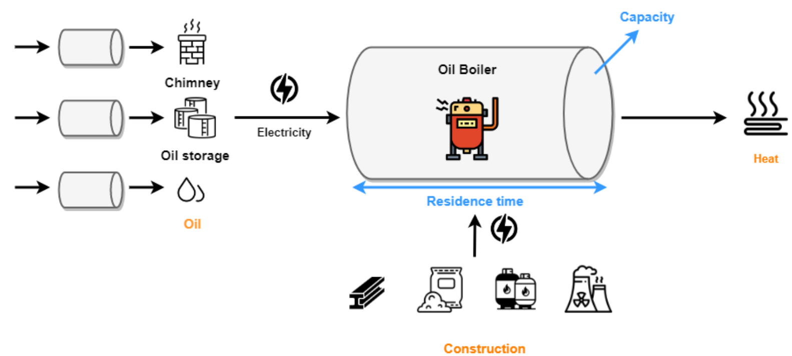
Double counting removal

The Central Product Classification (CPC) is a product classification for goods and services promulgated by the United Nations Statistical Commission.

Double counting removal flowchart[1]



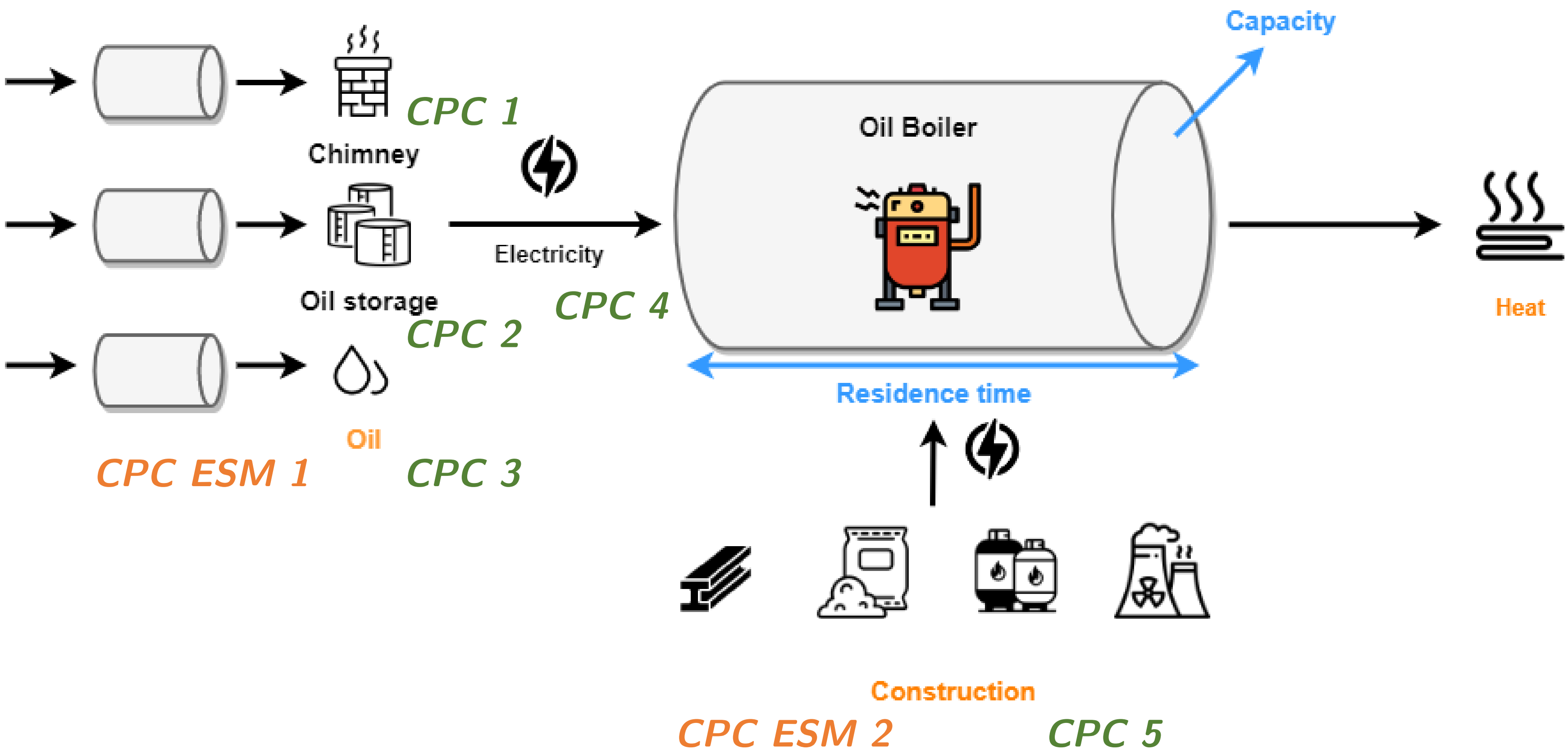




[1] M. Souttre, Mescal — mescal. [Online]. Available: https://mescal.readthedocs.io/en/latest/index.html

Double counting removal

Oil Boiler Example



L = [CPC ESM 1, CPC ESM 2]

CPC 3 and CPC 5 in L → *Construction & Oil flow amounts are set to 0*

Double counting removal

Files mapping

[1]

```
import ML_mapping
```

Executed at 2024.08.20 10:51:50 in 15s 359ms

[2]

```
self = ML_mapping.Mapping(reference_classification='CPC 2.1',
                          transformer_model='all-MiniLM-L6-v2',
                          number_of_guesses=5)
```

Executed at 2024.08.19 18:09:56 in 2m 9s 981ms

[3]

```
self.match_inputs(['OIL_Boiler'])
self.calculate_scores()
self.format_results()
```

Executed at 2024.08.19 18:09:56 in 77ms

5 rows 5 rows × 3 columns

product	order	code sector	sector	similarity
OIL_Boiler	1	33360	Gas oil	0.572717
	2	3336	Gas oil	0.572717
	3	33370	Fuel oils n.e.c.	0.522871
	4	3337	Fuel oils n.e.c.	0.522871
	5	21671	Olive oil, crude	0.492022

Methodology

Generalization

- ***Values In REHO database are without units***
- ***No LCA methods declared for impact categories***

World IMPACT + and Brightway

13 indicators to 29 indicators

Impact category	Unit	Abbrev
Climate change, ecosystem quality, long term	PDF.m2.yr	CCEQL
Climate change, ecosystem quality, short term	PDF.m2.yr	CCEQS
Climate change, ecosystem quality, long term, fossil and biogenic	PDF.m2.yr	CCEQLB
Climate change, ecosystem quality, short term, fossil and biogenic	PDF.m2.yr	CCEQSB
Climate change, human health, long term	DALY	CCHHL
Climate change, human health, short term	DALY	CCHHS
Climate change, human health, long term, fossil and biogenic	DALY	CCHHLB
Climate change, human health, short term, fossil and biogenic	DALY	CCHHSB
Freshwater acidification	PDF.m2.yr	FWA
Freshwater ecotoxicity, long term	PDF.m2.yr	FWEXL
Freshwater ecotoxicity, short term	PDF.m2.yr	FWEXS
Freshwater eutrophication	PDF.m2.yr	FWEU
Human toxicity cancer, long term	DALY	HTXCL
Human toxicity cancer, short term	DALY	HTXCS
Human toxicity non-cancer, long term	DALY	HTXNCL
Human toxicity non-cancer, short term	DALY	HTXNCS
Ionizing radiation, ecosystem quality	PDF.m2.yr	IREQ
Ionizing radiation, human health	DALY	IRHH
Land occupation, biodiversity	PDF.m2.yr	LOBDV
Land transformation, biodiversity	PDF.m2.yr	LTBDV
Marine acidification, long term	PDF.m2.yr	MAL
Marine acidification, short term	PDF.m2.yr	MAS
Marine acidification, long term, fossil and biogenic	PDF.m2.yr	MALB
Marine acidification, short term, fossil and biogenic	PDF.m2.yr	MASB
Marine eutrophication	PDF.m2.yr	MEU
Ozone layer depletion	DALY	OLD
Particulate matter formation	DALY	PMF
Photochemical oxidant formation	DALY	PCOX
Terrestrial acidification	PDF.m2.yr	TRA
Thermally polluted water	PDF.m2.yr	TPW
Water availability, freshwater ecosystem	PDF.m2.yr	WAVFWES
Water availability, human health	DALY	WAVHH
Water availability, terrestrial ecosystem	PDF.m2.yr	WAVTES
Total ecosystem quality	PDF.m2.yr	TTEQ
Total human health	DALY	TTHH
Total ecosystem quality, fossil and biogenic	PDF.m2.yr	TTEQB
Total human health, fossil and biogenic	DALY	TTHHB

Methodology

Normalization

MOO

$$Objective = \sum w_i X_i$$

$$X_{normalized} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

- ***Xmin can be easily obtained by changing the objectives***
- ***Xmax can be obtained by optimizing other objectives***

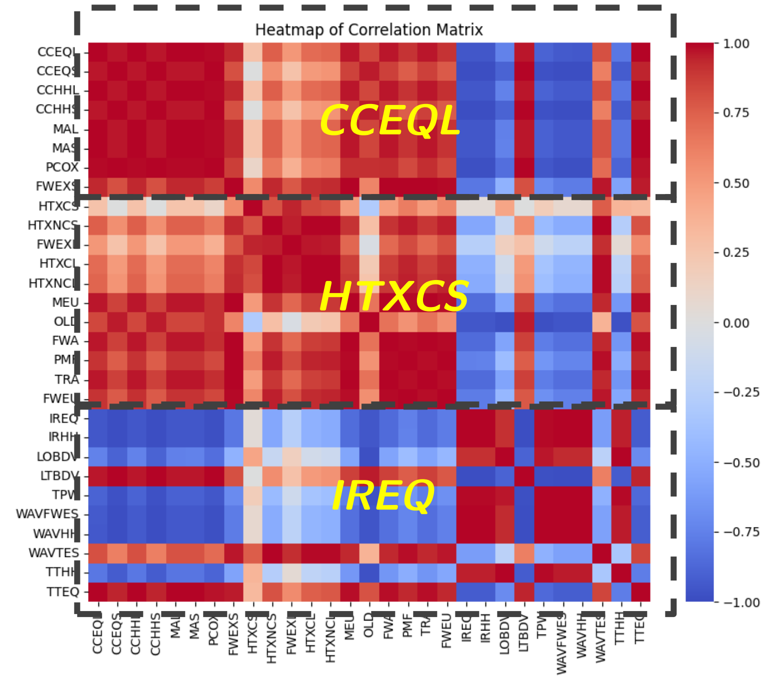
29 times for optimization

Pearson Correlation

$$r_{XY} = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}}$$

- ***The dataset has been grouped into three clusters using K-means, and their dynamic changes effectively reflect the overall variations in the dataset***

3 times for optimization

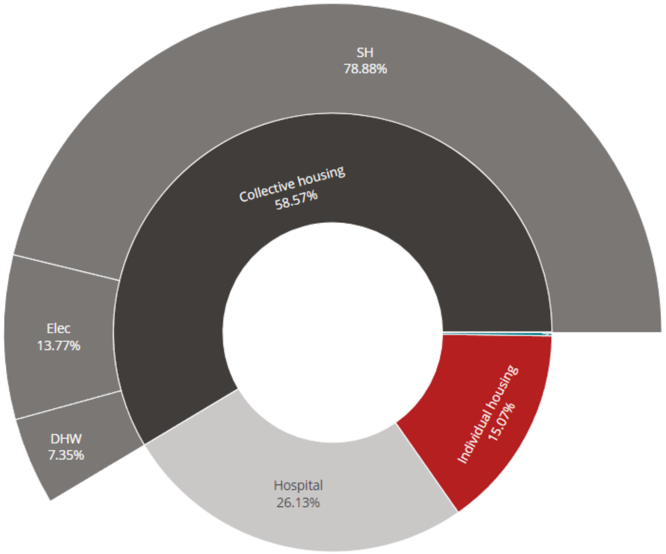


Case Study

Sion

Sion, a city in Switzerland, already has building datasets integrated within REHO. This makes it an ideal starting point for validating the new methodology and assessing its generalization capabilities.

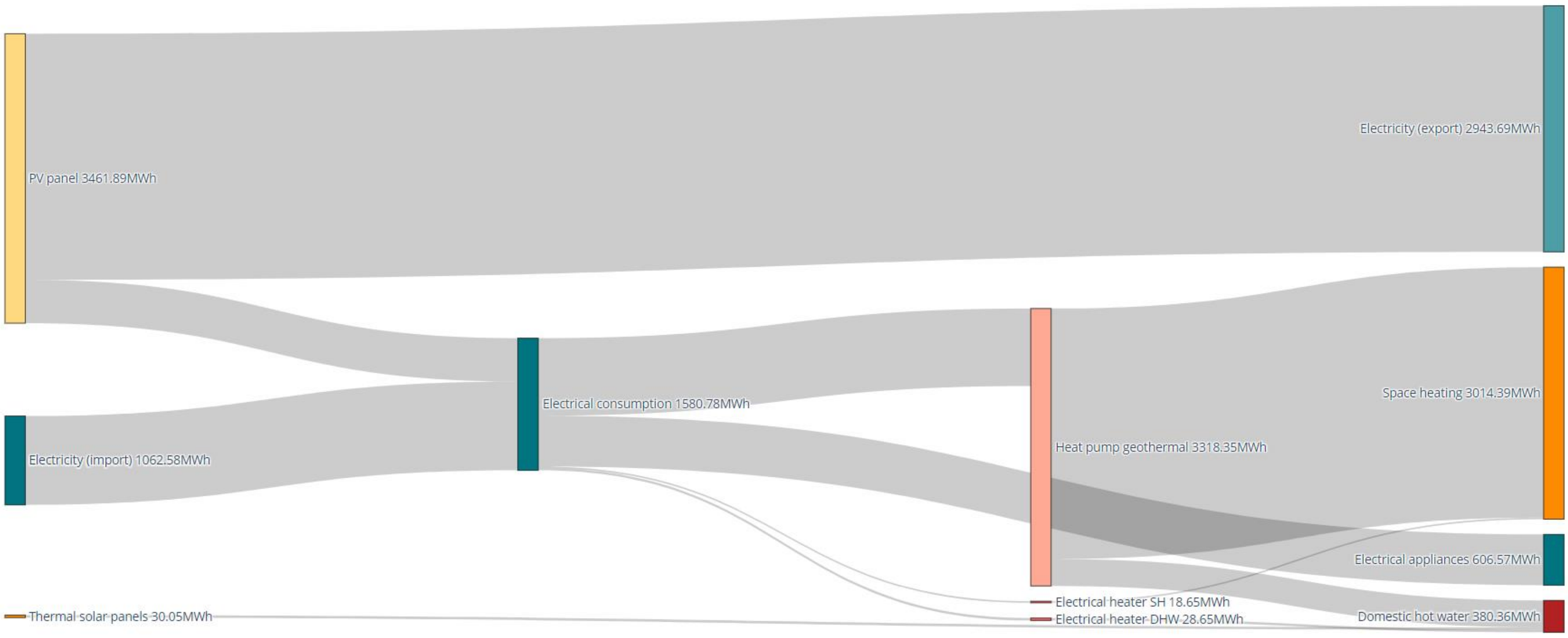
Comparative Analysis Between the Old and New Methodology



- ***Scenario:*** *40 buildings in Sion, no requirements for equipments*
- ***Objective:*** *minimize GWP*
- ***The primary contributor*** *to the EUDs is collective housing, which accounts for 78.88%. space heating(SH), 13.77% electricity (elec), and 7.00% domestic hot water (DHW)*

In original REHO, most of the "fixed environmental impacts" are set to a small value like 0.0001, which can be replaced by operation LCA. Thus it allows us to compare different methodologies by fixing the dataset.

Both of the methodologies outcome the Sankey below:



- ***This outcome implies that both methodologies yield the same optimal configuration of the same district energy system****

Results

Sion

Old Methodology:

```
0 simplex iterations
              GWP
0 -122008.748889
```

GWP_op	GWP_constr
-244549.6937	122466.0784

New Methodology:

```
0 simplex iterations
              GWP
0 -121598.471405
```

GWP_op	GWP_constr	GWP_res
346.1894292	122459.106	-244549.6937

As expected, the final numerical result is different

The LCA methodology is successfully integrated

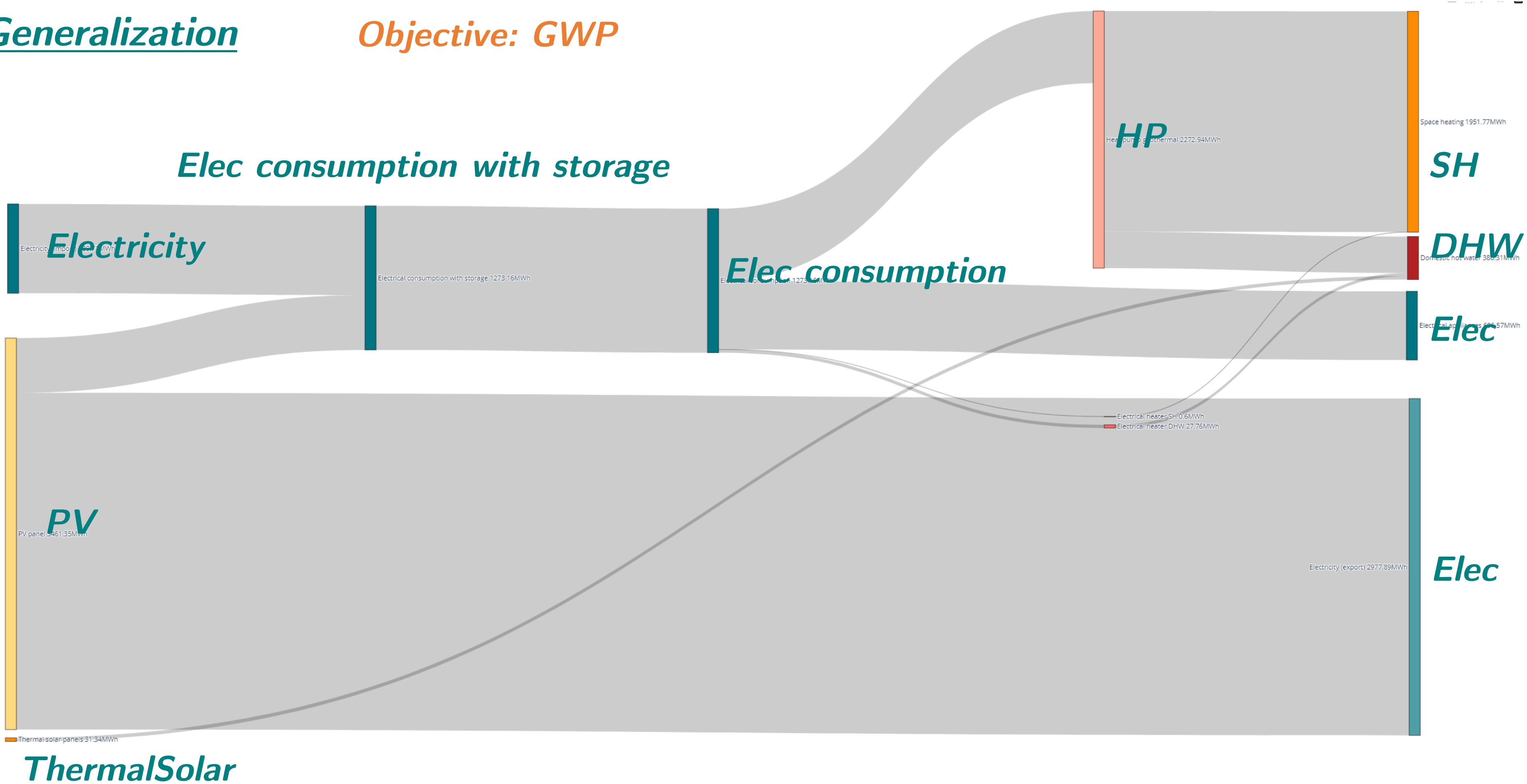
- ***The configuration is the same***
- ***The GWP_op from the old methodology is the same with the GWP_res in new methodology***
- ***GWP_constr is different for different ways of calculating construction***

Case Study

Sion

Generalization

Objective: GWP



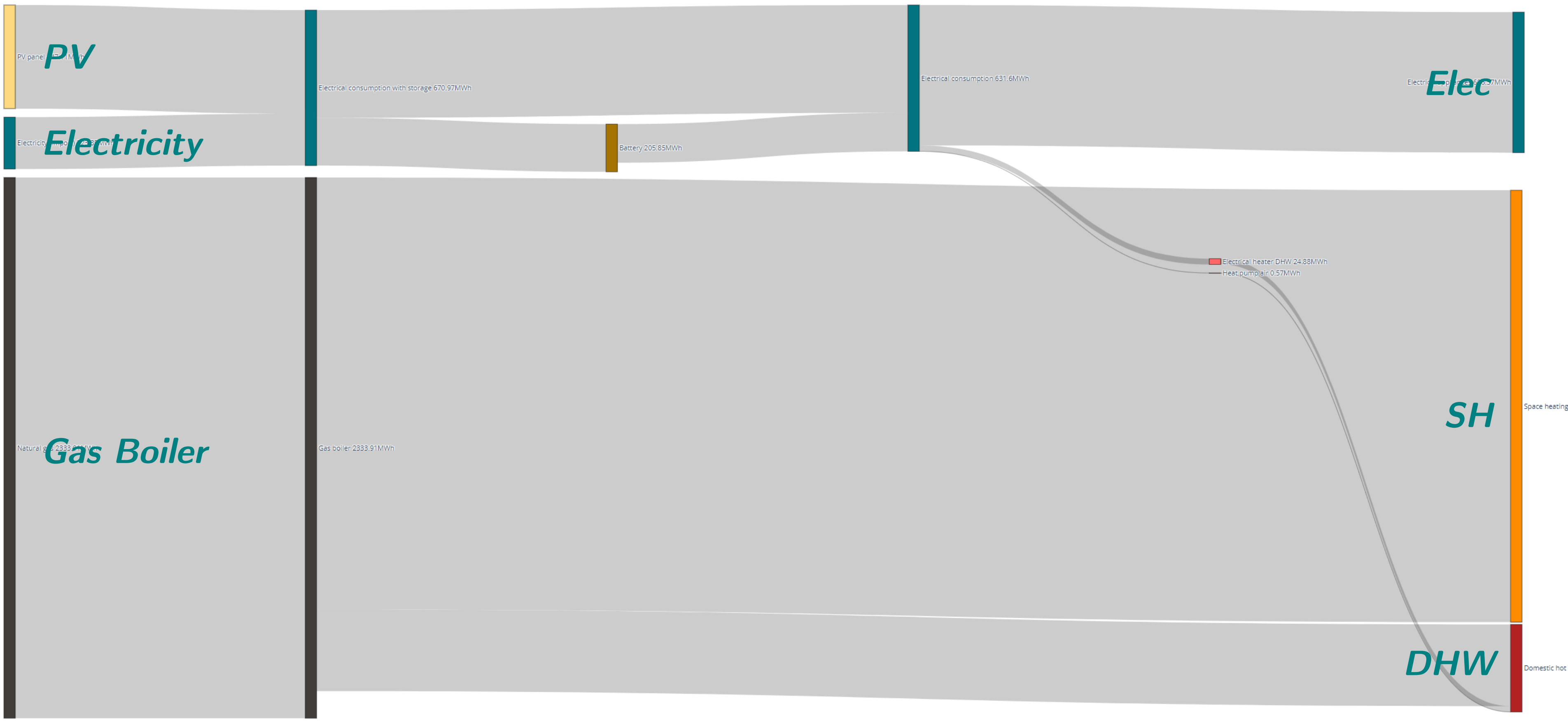
This demonstrates that when optimizing for GWP, photovoltaic (PV) systems are extensively utilized, while fossil-based technologies are excluded in order to minimize global warming potential. The GWP result is around −96, 136kg CO2

Case Study

Sion

Generalization **Objective: LOBDV**

Elec consumption with storage



The energy system limits the use of PV panels due to their large environmental impacts on land occupation. Instead, gas boilers are widely used to provide heat, reducing the reliance of electricity on heat pumps that would otherwise require significant land area to operate.

Lugaritz-Matía Community in Spain

After integrating the LCA framework successfully, a real case study is conducted:

- ***Composed of 3 buildings:***
    - ***Birmingham Hospital***
    - ***Rezola Nursing Home***
    - ***Lugaritz Nursing Home***

2 Case Study are conducted:

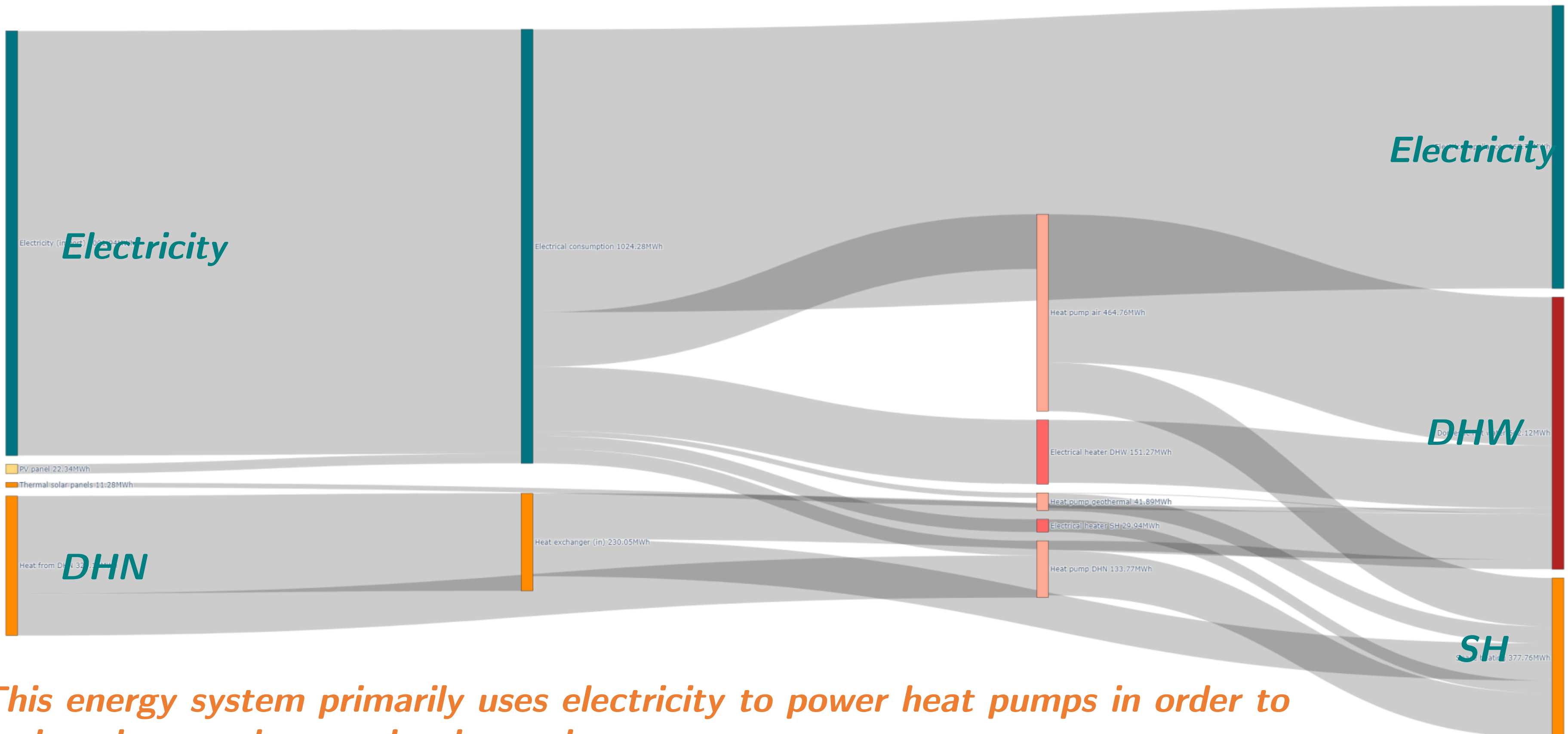
- ✓ ***Simulation of current energy system;***
- ✓ ***Optimization for fossil-free scenario.***

Results

Lugaritz-Matía Community in Spain

Current scenario simulation (with original dataset)

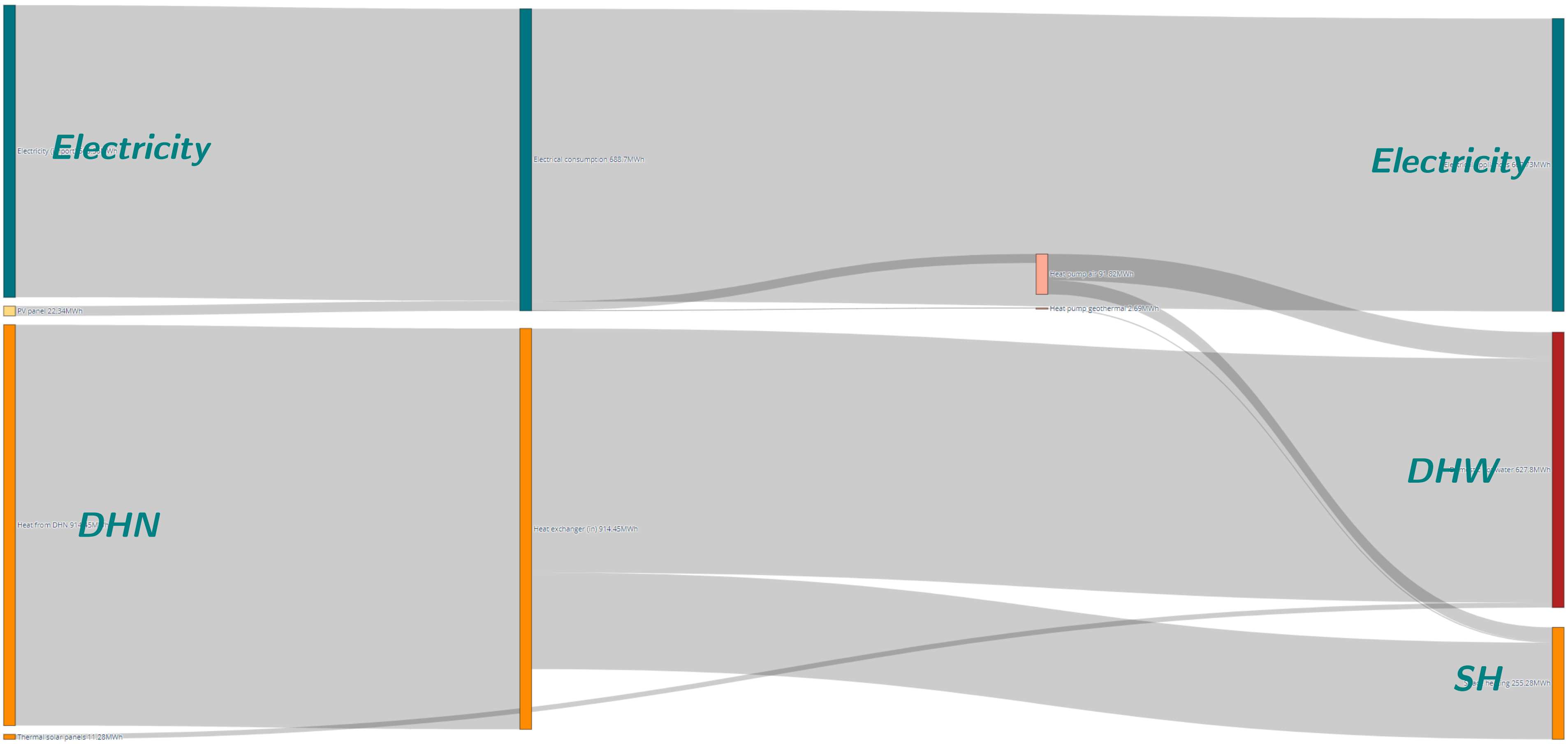
In the current scenario, multiple technologies' capacities are fixed based on datasets from the pilot, including: 'HeatPump_Air', 'HeatPump_Geothermal', 'NG_Boiler','OIL_Boiler', 'ThermalSolar', and 'PV'. And district heating network (DHN) is used.



This energy system primarily uses electricity to power heat pumps in order to produce heat and meet the demand

Lugaritz-Matía Community in Spain

Current scenario simulation (with new dataset)

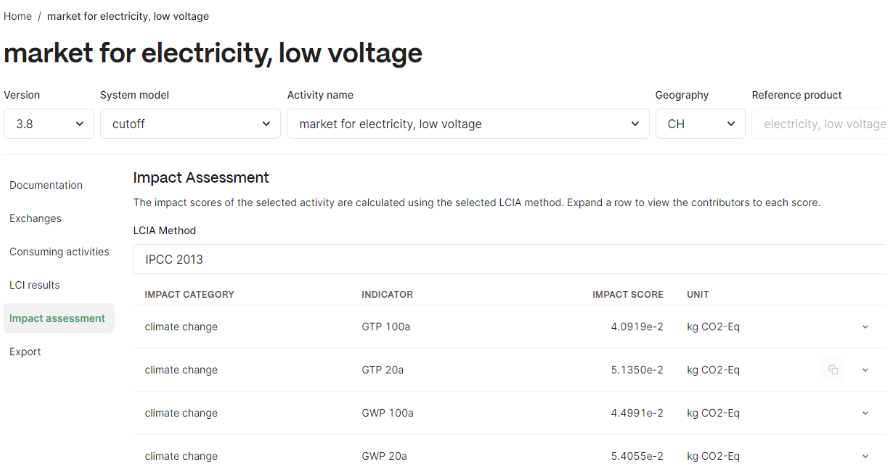


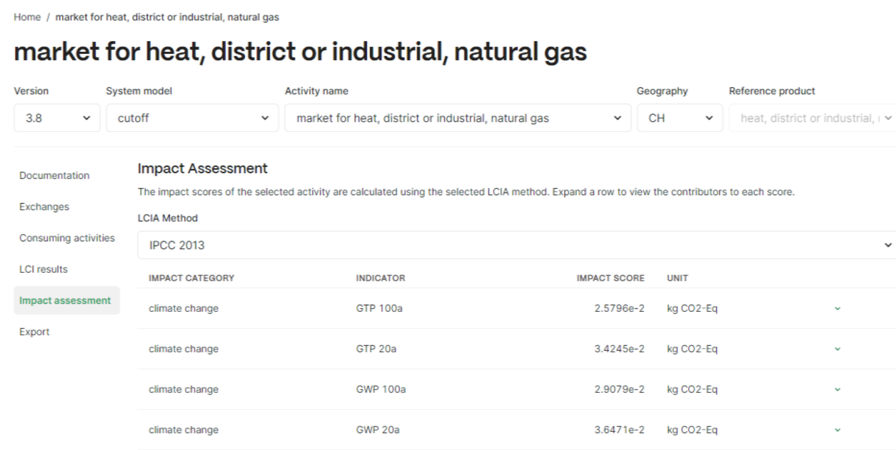
This energy system primarily directly uses DHN to produce heat and meet the demand

Lugaritz-Matía Community in Spain

Comparison

- ***The root cause of this behavioral difference is that, in the original dataset, heat is more expensive than electricity in terms of GWP, whereas the new database does not reflect this***





*GWP100a: 4.4991*e^(-2)*

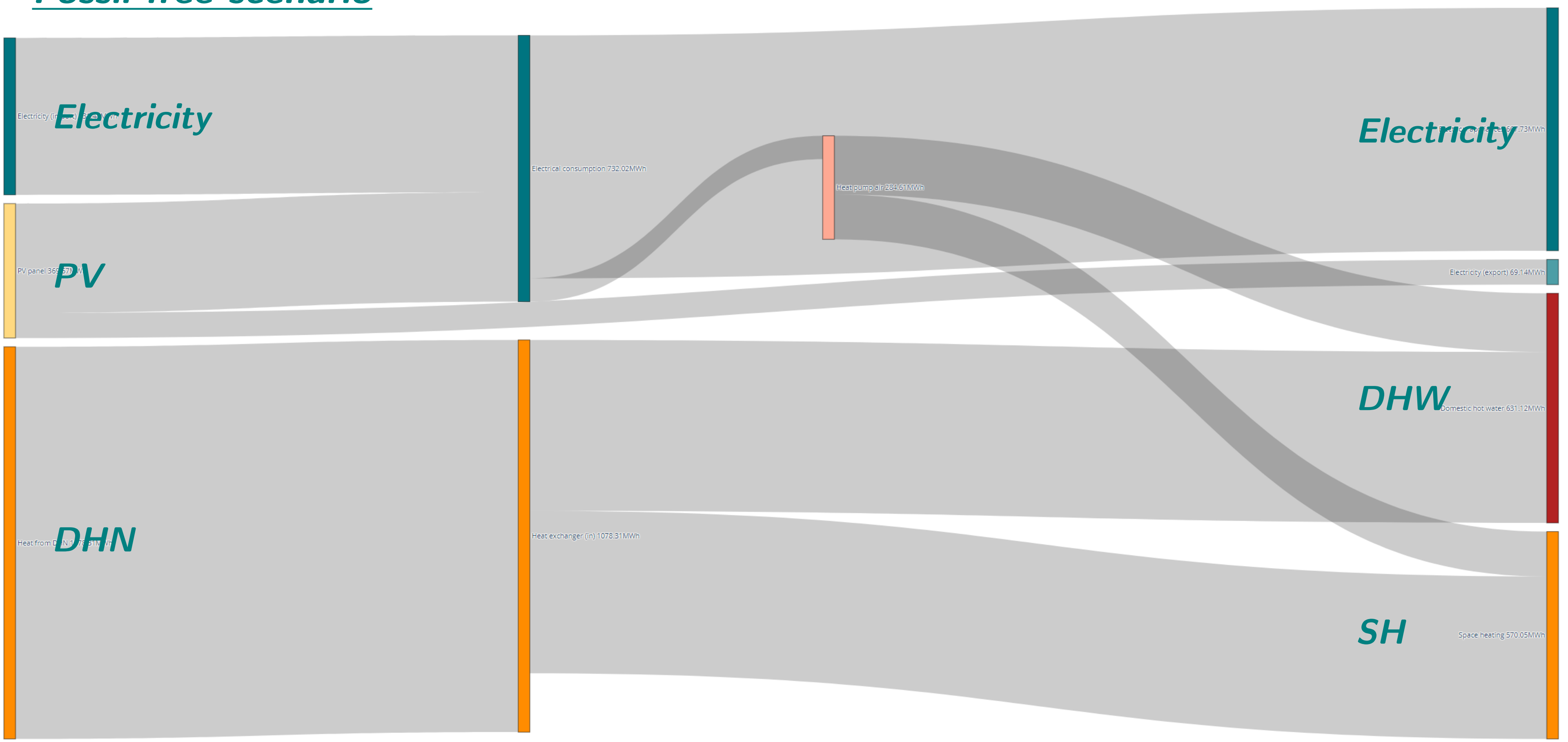
*GWP100a: 2.9079*e^(-2)*

- ***Due to the direct and more efficient use of heat, the GWP of heat is indeed lower than that of electricity, as is also evident from the Ecoinvent database***

Results

Lugaritz-Matía Community in Spain

Fossil-free scenario



- ***Photovoltaic (PV) panels have fully replaced fossil fuel-based technologies in the energy system.*** ***Over the course of a year, the PV system generates 369.67 MWh, with a portion used for electricity, while 284.61 MWh supports domestic hot water and space heating.***
- ***DHN*** ***still plays an major role in satisfying the heat demand.***

Accomplishments and Areas for Improvement

Accomplishments

- ***Implementation of a New LCA Methodology***
- ***Improvement in Data Accuracy (Generalized and Double counting removed LCA database)***
- ***Normalization***
- ***Integration and Validation of the New LCA Framework***
- ***Real-World Application and Insights***

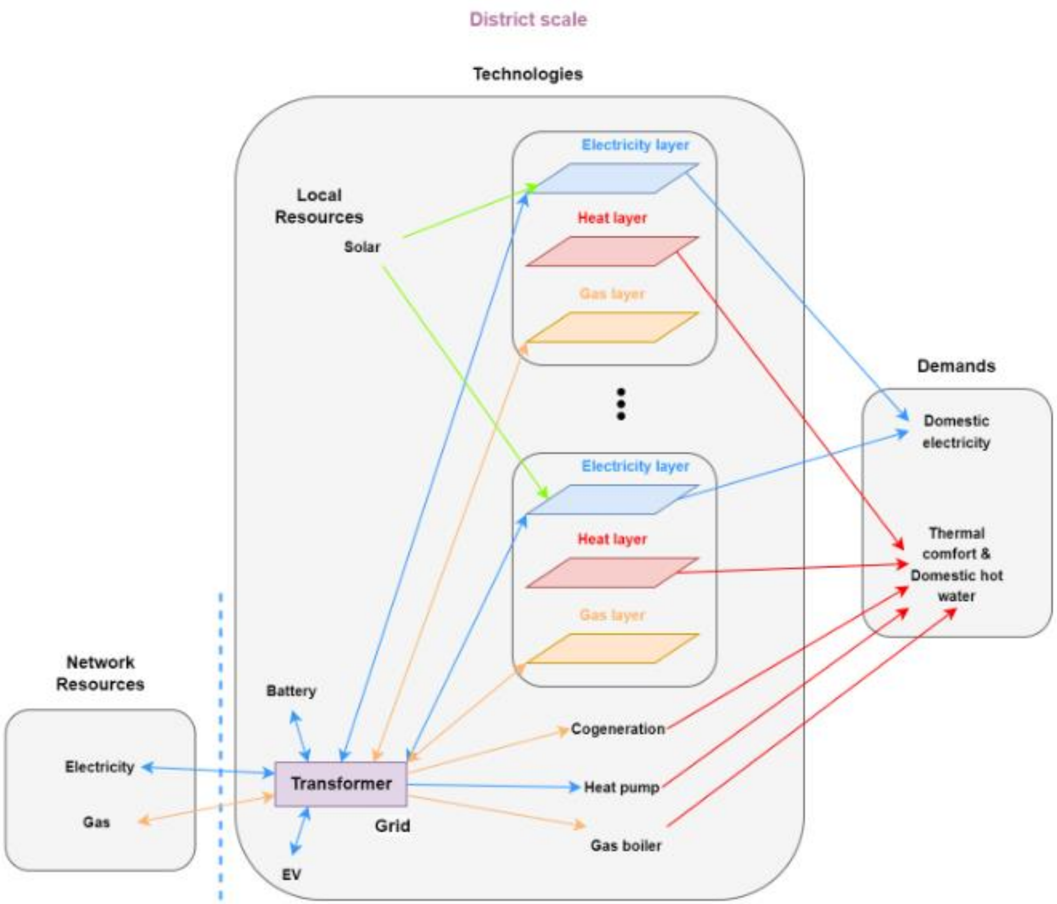
Areas for Improvement

- ***Data Availability Gap***
- ***District Heating Network Generalization Challenges***
- ***Double Counting Removal Database Globalization***

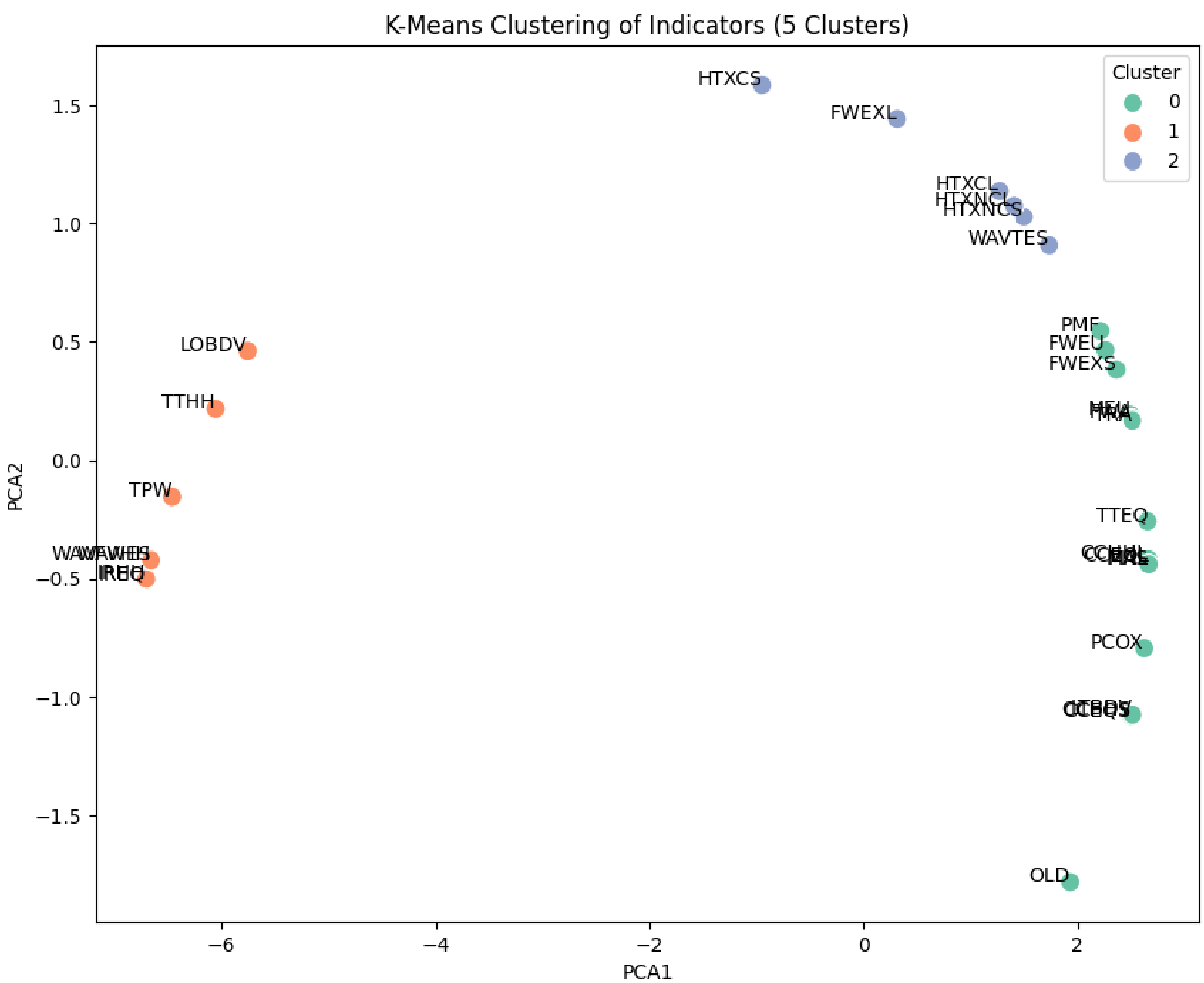
THANK YOU FOR YOUR ATTENTION!

For all the relevant codes, please refer to:
https://github.com/zhichuanma/REHO/tree/LCA_integration

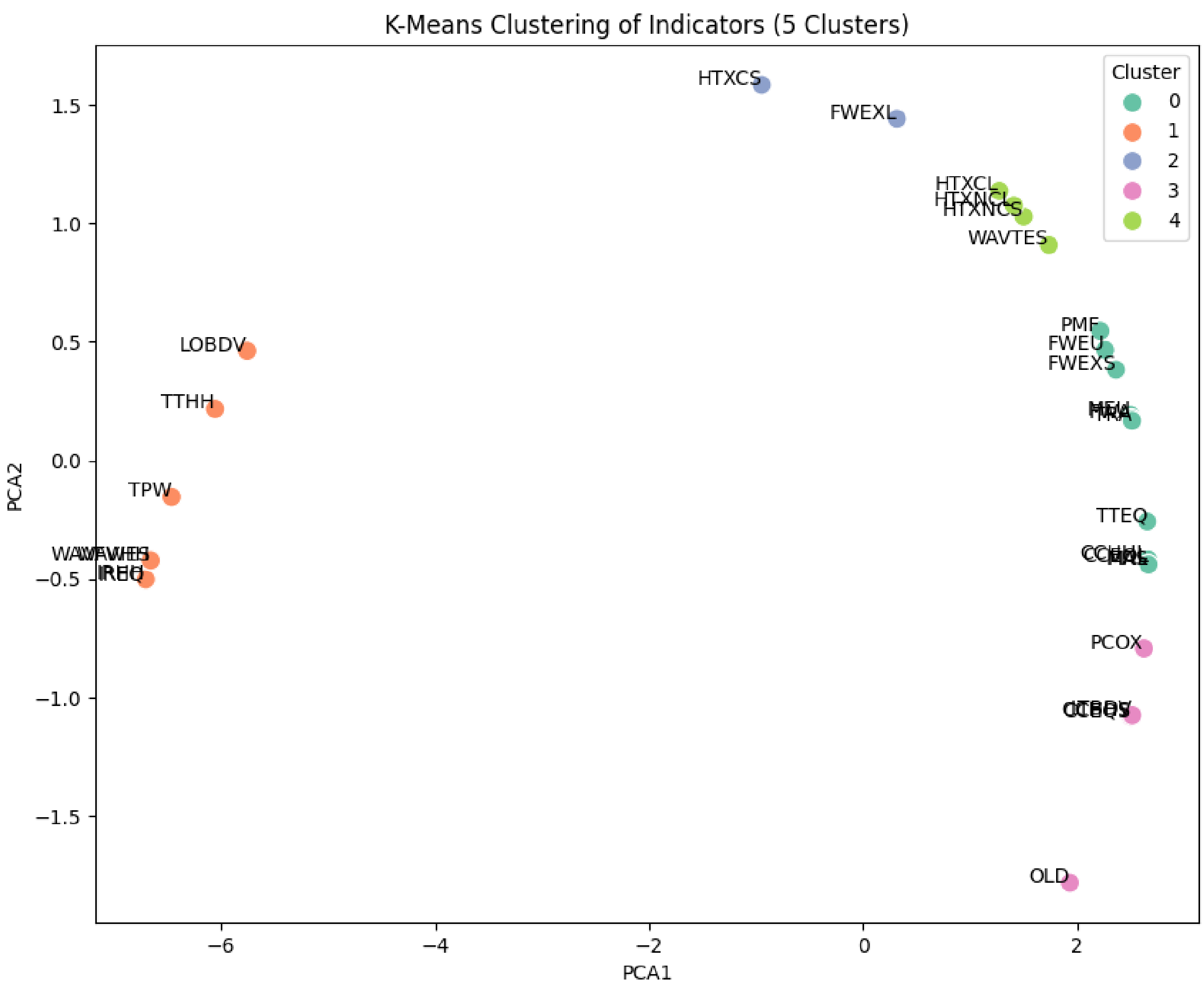
District level energy system



PCA 3 clusters



PCA 5 clusters



Appendix

VEO Spain pilot datasets-1

	PARAMETERS	HISTORICAL	Berminghan	Rezola	Lugaritz
NAME	Building identifier	NO	BER	REZ	LUG
TYPE	Building type	NO	Hospital	Nursing home	Nursing home (54 apartments + 40 day beds) + Office building
ADDRESS	Town or address	NO	San Sebastián, Basque Country (Spain)Matia - Bermingham Ospitalea	an Sebastián, Basque Country (Spain)Centro Gerontológico Julián Rezol	ebastián, Basque Country (Spain)Matia - Lugaritz - Babesdun Etxebi
COORDINATES	Latitude	NO	43,3038	43,3034	43,3045
	Longitude	NO	-2,0014	-2,0031	-2,0024
NOTE	If any additional information is needed	NO	The DH is located in Lugaritz building	The DH is located in Lugaritz building	The DH is located in Lugaritz building
GEOMETRY	Floor number	NO	9	4	7
	Height up to the last ceiling [m]	NO	24,65	11	19,5
	Floor area [m2]	NO	18 000	Floor 0: 1,459.42; Floor 1: 1,589.35;Floor 2: 1,517.53; Floor 3: 742.92	,269.87; Floor 2: 3,214.9; Floor 3: 3,335.5; Floor 4: 3,244.18; Floor
	Vertical facades area [m2]	NO	25 932	1 235	6 424
	Vertical windows area [m2]	NO	300	68	163
	Solar vertical facades area [m2]	NO	12 966	600	3 200
	Solar roof area [m2]	NO	330	800	220
EPB	Construction period [y]	NO	2011	1989	2023
	Yearly electricity demand [kWh/y]	NO	368,000 for heating	N/A	30 for cooling
	Yearly heating demand [kWh/y]	NO	1 352 000	979 000	910 000
	Yearly DHW demand [kWh/y]	NO	425 000	246 000	56 940
	Averaged thermal transmittance [kW/m2·K]	NO	Facade: k=0.66 Roof: k=0.38	Facade: k=1.8 Roof: k=1.4	Facade: k=0.27 Roof: k=0.22
	Thermal specific capacity [Wh/m2·K]	NO			
USAGE		NO	[Hospital, Swimming pool]	Residential (Collective housing)	[Residential (Collective housing), Administrative]
	Percentage of each utilisation [%]	NO	[87.5, 12.5]	100	[70, 30]
	Average users of the building	NO	336	143	148
	Electrical appliances consumption (Low, Medium, High)	NO	High	High	High
THERMAL	Heating technology (indicate all available)	NO	[DH(Biomass, Condensing boiler), Conv. boiler, ASHP, Solar thermal]	[DH(Biomass, Condensing boiler), Conv. boiler, Condensing boiler]	[DH(Biomass, Condensing boiler), GSHP, Chiller recov.]
	Heating technology power [kW]	NO	[DH(500+300, 620+620), 270+270+270, 16, 40x0.4]	[DH(500+300, 620+620), 270, 115]	[DH(500+300, 620+620), 160, 14.5]
	Heating technology energy [kWh] (include link to time seri	YES	Datos Berminghan desde SCadaDatos Lugaritz desde SCada	Datos Rezola desde SCada Datos Lugaritz desde SCada	Datos Lugaritz desde SCada
	Heating storage volume [m3]	NO	2x2[DH(4, N/A), N/A, N/A, 2.5]	[DH(4, N/A, N/A, N/A), N/A, N/A]	3.1[DH(4, N/A, N/A, N/A)]
	Heating storage maximum power [kW]	NO			
	Heating storage capacity [kWh]	NO			
	DHW technology (indicate all available)	NO	[DH(Biomass, Condensing boiler), Conv. boiler, ASHP, Solar thermal]	[DH(Biomass, Condensing boiler), Conv. boiler, Condensing boiler]	[DH(Biomass, Condensing boiler), GSHP, Chiller recov.]
	DHW technology power [kW]	NO	[DH(500+300, 620+620), 270+270+270, 16, 40x0.4]	[DH(500+300, 620+620), 270, 115]	[DH(500+300, 620+620), 160, 14.5]
	DHW technology energy [kWh] (include link to time series)	YES	Datos Berminghan desde SCadaDatos Lugaritz desde SCada	Datos Rezola desde SCada Datos Lugaritz desde SCada	Datos Lugaritz desde SCada
	DHW storage volume [m3]	NO	2x2[DH(4, N/A), N/A, N/A, 2.5]	2x0.8[DH(4, N/A), N/A, N/A]	3.1[DH(4, N/A), N/A, N/A]
	DHW storage maximum power [kW]	NO			
	DHW storage capacity [kWh]	NO			
	Cooling technology (indicate all available)	NO	N/A	N/A	[Chiller, GSHP]
	Cooling technology power [kW]	NO	N/A	N/A	[218, 141]
	Cooling technology energy [kWh] (include link to time seri	YES	N/A	N/A	Datos Lugaritz desde SCada
	Cooling storage volume [m3]	NO	N/A	N/A	1.5[N/A, N/A]
	Cooling storage maximum power [kW]	NO	N/A	N/A	N/A
	Cooling storage capacity [kWh]	NO	N/A	N/A	N/A
	Target or ideal internal temperature [°C]	NO	21 (Winter) / 25 (Summer)	21 (Winter) / 25 (Summer)	21 (Winter) / 25 (Summer)
	Heating supply temperature [°C]	NO	80 (Winter) / 70 (Summer)	80 (Winter) / 70 (Summer)	80 (Winter) / 70 (Summer)
	Heating return temperature [°C]	NO	60 (Winter) / 50 (Summer)	60 (Winter) / 50 (Summer)	60 (Winter) / 50 (Summer)

Appendix

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	Cooling supply temperature [°C]	NO	7	7	7
	Cooling return temperature [°C]	NO	12	12	12
HEAT/RECOVERYTECHN	Waste heat sources (indicate all available)	NO	N/A	N/A	Heat recovery from chiller / Heat recovery from air extraction
	Heat transfer fluid to be recovered (Liquid water, Steam, A	NO	N/A	N/A	Water / Air
	Heat transfer fluid temperature [°C] (include link to time se	YES	N/A	N/A	35-40 Datos Lugaritz desde SCada
	Heat transfer fluid pressure [bar]	NO	N/A	N/A	1
	Heat transfer fluid flow (include link to time series)	YES	N/A	N/A	Datos Lugaritz desde SCada
	Distance between heat source and final use	NO	N/A	N/A	
	Space available next to the heat source	NO	N/A	N/A	
	Recovery technologies already installed (indicate all availat	NO	N/A	N/A	DH(Chiller heat recovery)
	Recovery technology power [kW]	NO	N/A	N/A	10
	Recovery technology energy [kWh] (include link to time se	YES	Datos Berminghan desde SCadaDatos Lugaritz desde SCada	Datos Rezola desde SCada Datos Lugaritz desde SCada	Datos Lugaritz desde SCada
ELECTRIC	Electricity consumption profile [kWh] (include link to time	YES	N/A	N/A	N/A
	PV capacity [kW]	NO	N/A	N/A	16 335
	PV production [kWh] (include link to time series)	YES	N/A	N/A	17,839 Datos Lugaritz desde SCada
	Wind turbines capacity [kW]	NO	N/A	N/A	N/A
	Wind turbines production [kWh] (include link to time serie	YES	N/A	N/A	N/A
	Battery maximum discharge power [kW]	NO	N/A	N/A	N/A
	Battery capacity [kWh]	NO	N/A	N/A	N/A
	Battery minimum SoC fixed [%] / [kWh]	NO	N/A	N/A	N/A
	Battery maximum SoC fixed [%] / [kWh]	NO	N/A	N/A	N/A
	Battery SoC [%] / [kWh] (include link to time series)	YES	N/A	N/A	N/A
	EV charger power [kW]	NO	N/A	N/A	N/A
	EV battery capacity [kWh]	NO	N/A	N/A	N/A
	EV minimum SoC fixed [%] / [kWh]	NO	N/A	N/A	N/A
	EV maximum SoC fixed [%] / [kWh]	NO	N/A	N/A	N/A
	EV SoC [%] / [kWh] (include link to time series)	YES	N/A	N/A	N/A
	Other [?]	NO	N/A	N/A	N/A
GRID	Feed-in tariff rate [€/kWh]	NO	N/A	N/A	N/A
	Energy price of the community member [€/kWh]	NO	N/A	N/A	N/A
	Grid tariffs / network costs [€/kWh]	NO	N/A	N/A	N/A
	Type of trading allowed if any	NO	N/A	N/A	N/A