IntegrCiTy

Decision-support environment for planning and integrating multi-energy networks and low-carbon resources in cities

Integrated method for systematic scenario generation using multi-objective optimization

Deliverable 4.3 Report

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Nomenclature

Acronyms

BES	Building energy system
CAPEX	Capital expenditure
CDD	Cooling degree day
CHP	Combined heat and power
DRY	Design reference year
DES	District heating system
DHC	District heating and cooling
DHN	District heating network
DWT	Domestic hot water tank
ELDC	Error in load duration curve
ET	Energy technology
G2P	Gas to power
GHI	Global horizontal irradiance
GM	Grid multiple
HDD	Heating degree day
HHS	Hydronic heating system
HWT	Hot water tank
LPEM	Low temperature proton exchange membrane
MILP	Mixed-integer linear programming
OPEX	Operational expenditure
P2G	Power to gas
PI	Process integration
PV	Photovoltaic
SOFC	Solid oxide fuel cell

Sets

$\boldsymbol{B}$	Building
$\boldsymbol{K}$	Temperature level
$\boldsymbol{T}$	Time (hour)
$\boldsymbol{P}$	Period (day)
$\boldsymbol{U}$	Utility types
$\boldsymbol{\Sigma}$	Decision variables

Subscripts/Superscripts

$+/-$	Incoming/outgoing flow
amb	Ambient
b	Building
c	Cooling
cl	Cluster
d	Day
el	Electrical
$grid$	Electrical grid or thermal network
h	Heating
k	Heat cascade interval index
p	Operating period (typical day)
t	Time (hour)
u	Unit, device

Symbols

c_1, c_2	Network cost parameters
$\dot{E}_b^-$	Building uncontrollable load profile
$\dot{E}_{grid}$	Power profile to/from the grid

ϵ_I	Investment cost \epsilon-constraint
ϵ_{GM}	Grid Multiple \epsilon-constraint
d_p	Period duration
d_t	Timestep duration
E	Electrical energy
f_u	Unit size factor
F_u^{min}	Device minimal sizing values
F_u^{max}	Device maximal sizing values
H	Chemical gas–power flows
i	Interest rate
$I_{1,u}, I_{2,u}$	Investment cost parameters [CHF, CHF/m]
L^{DHN}	Network length [m]
$\dot{m}$	Mass flow
N	Project horizon
N_u	Unit lifetime
n	Total number
op	Grid energy tariffs
Q	Thermal energy
$Q_{u,h}^{+}$	Heat demand of utility (u_c)
$Q_{u,h}^{-}$	Released heat of utility (u_h)
R	Heat cascade residual
r	Project interest rate
rep_u	unit purchases over N
ρ	Density [kg/m^3]
s	Silhouette coefficient
T	Temperature
τ	Annualization factor

u_c	Cold utility
u_h	Hot utility
v	Velocity [m/s]
y_u	Unit existence
$y_{u,p,t}$	Logical state on/off of unit u

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1. Introduction

Multi-energy networks are going to play an important role in dense areas (cities) for the energy transition and the integration of renewable energy sources [1]. The IntegrCiTy project uses a co-simulation approach at urban scale in order to maximize the penetration of renewable energy. The concept joins independent software and tools to simulate the dynamics and impacts of each urban sub-system simultaneously. However, if co-simulation tools are able to predict accurately the operation of urban multi-energy system, they don't intend to provide the design of energy system. A three-step method is therefore proposed to generate and identify the feasible alternatives for the energy supply of urban areas (Figure 1), taking into consideration the multi-energy network infrastructure.

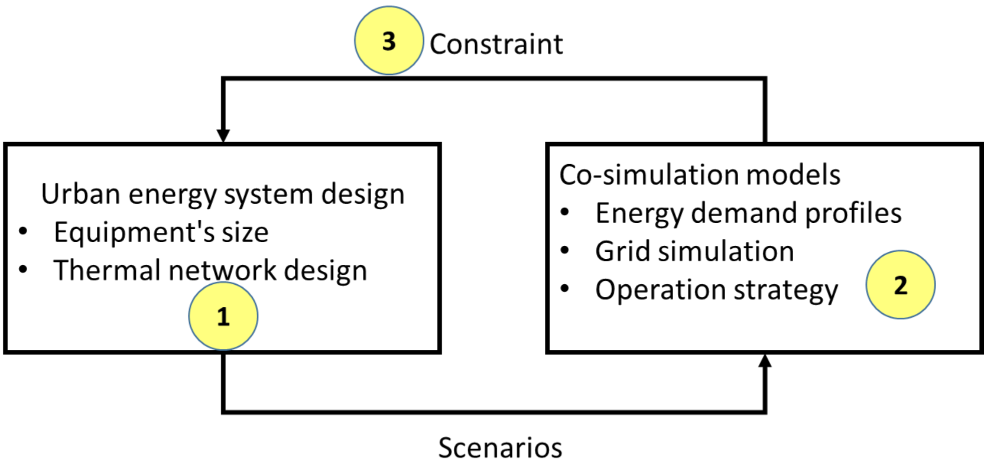

Figure 1: Principle of the three-step methodology

This report focused on the description of a method using energy integration and multi-objective optimization techniques to systematically generate urban energy system design including the definition of multi-energy networks, size of the energy conversion equipment and access to local resources. The originality of the method lie in the combination of recently developed method and tools for:

1. the generation of scenario using multi-objective optimisation and meta-models for building energy system (BES) based on a design and scheduling procedure developed by [2] and [3];
2. the identification of the key bottlenecks of multi-energy networks using a power flow solver developed in IntegrCiTy [4];
3. the application of co-simulation principles [5][6] and models to multi-energy urban systems, implemented in IntegrCiTy (obnl)[1].

Solving simultaneously the design and operation of complex urban energy systems, such as the one proposed in Figure 2, is a challenging task, which can be achieved, in a first approach, using process integration [7]. Process integration (PI) techniques [8] based on pinch analysis methods [9] are a mature technology to evaluate the optimal thermo-economic size and operation of steady-state heat and power systems, without examining in detail the complexity of the heat exchanger configuration. Since the introduction of mixed integer linear programming (MILP) to model heat and material balances, design equations and physical and logical constraints [10], the method- ology has been subject to continuous

[1] OBvious Node Link co-simulator https://github.com/IntegrCiTy/obnl

developments [11] [12]. For instance, multi-period problems can be solved as a succession of steady-state operations assuming constant or piece-wise linearized costs and efficiency parameters around the equipment range of operation [13].

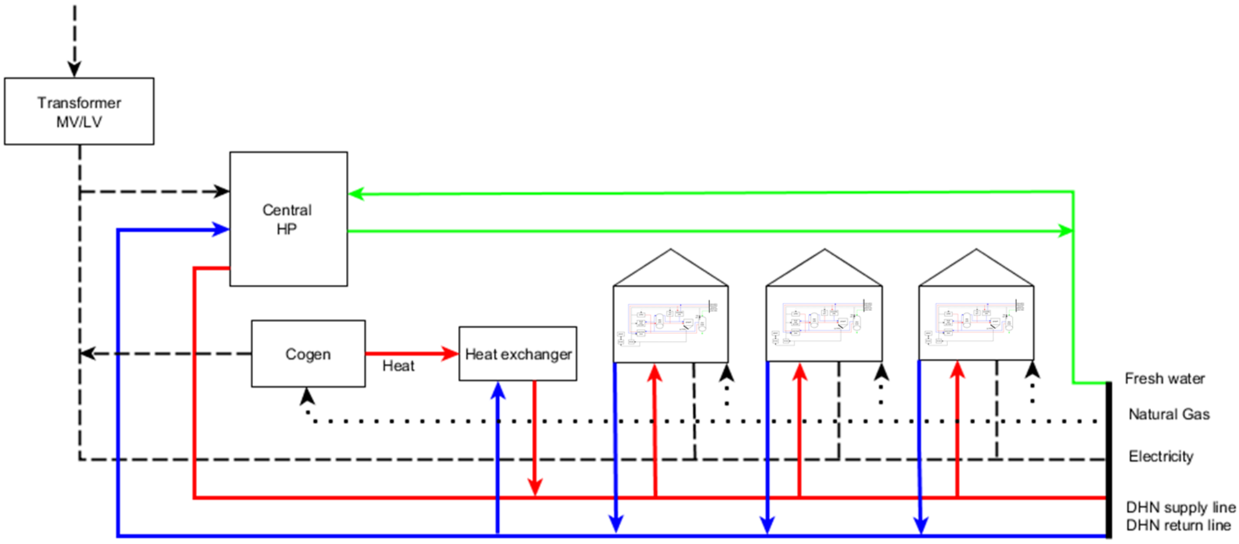

Figure 2: Superstructure of the district multi energy system including meta-models for the energy technologies in buildings

Combined with network's load flow simulation tools and co-simulation platform, the proposed method allows to generate and evaluate alternative design solutions for multi-energy urban systems considering topological and operational constraints of the multi-energy networks.

2. Methodology

A three-step method (Table 1) is proposed to identify the feasible alternatives for the energy supply of urban areas, taking into consideration the infrastructure of the multi-energy network.

The aim of the first phase (§2.1) is to generate scenarios covering a wide range of possible configurations and values for the energy, environmental and economic key indicators [14]. At this stage, decision makers will be able to select conceptual designs that fit with their target perspective.

Table 1: Phase, tasks and tools of the three step method

Phase	Tasks	Tools
1. Conceptual design	• Energy integration • Preliminary design	Osmose
2. Pertinent design	• Bottleneck identification • Safe operation of the networks	Power flow
3. Final design	• Validation of the overall operation strategy • Multi-energy co-simulation	obnl

In the second phase (§2.2) the multi-energy distribution system is assessed using power flow analysis to ensure the safe operation of the networks. The proper operation of all the component of the final design (§2.3) is finally validated with the multi-energy co-simulation of the system.

2.1 Conceptual design of urban energy systems

The challenge behind the automatic generation of scenario at urban scale is to solve simultaneously the conceptual design and the hourly loads scheduling problems within acceptable computing time limits of a few seconds. Moreover, in order to ensure sufficient accuracy, the model must take into account:

- an optimal operation strategy considering the appropriate temperature level to provide thermal comfort in the building;
- the generation profiles with hourly time steps;
- part-load efficiencies and controlled start-up and shutdown of the equipment;
- the integration of centralized and decentralized energy technologies;
- the operation of thermal and electrical storage;
- the integration of constraint at building scale to favour grid friendly operation;
- the use of the thermal mass of the buildings as heat storage with variable indoor temperature;
- flexibility allowing straightforward integration of additional energy sink, source or storage such as power to gas (P2G), gas to power (G2P), residual heat source and energy storage;
- the automatic generation of alternatives designs.

To meet these challenges, the scenarios at district scale are systematically generated using multi-objective optimisation and process integration techniques to design decentralized and centralized energy systems.

The proposed method [3] generates various conceptual design of urban energy system without going into the detail of the energy network's topology. The method is characterised by the use of:

- process integration techniques based on a MILP formulation;
- data reduction techniques for the temporal, spatial and typological aspects;
- a two-level decomposition of the problem at building and district scale;
- meta-model of the building energy system (BES) obtained from parametric optimization;
- cyclic constraints for thermal and electrical storage;
- grid multiple constraint (GM) to limit the building power peaks;
- piece-wise linearization of efficiencies and distribution temperatures

The alternatives generated are compared with key performance indicators [14], such as CAPEX and OPEX. The method considers the access to the local resources as well as the mass and energy balance of the multi-energy networks, without taking into account flow constraints.

At district scale, process integration techniques implemented in OSMOSELua [15] (Figure 3) allow to find the optimal size and operation of the energy technologies. Effective problem solving is achieved using meta-models for the decentralized energy technologies in buildings. The meta-model results from the systematic generation of alternatives for decentralized energy technology (ET) type, sizes and operation using parametric optimization at building scale.

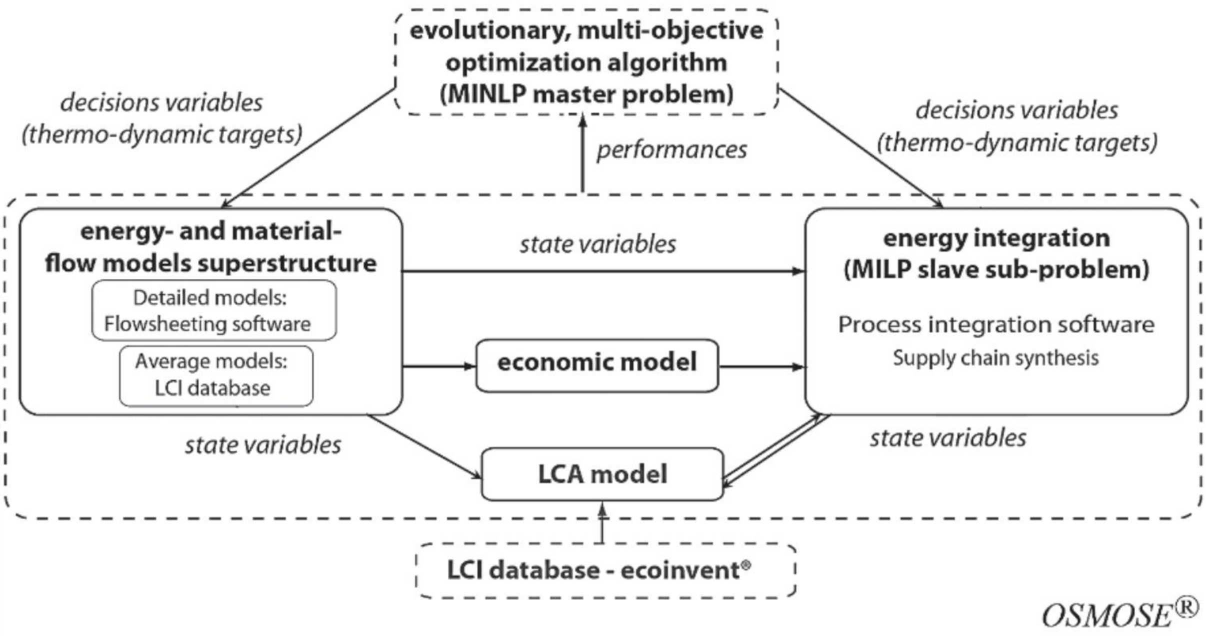

Figure 3: OSMOSE computational framework for energy system optimization [15]

2.2 Precise design through bottlenecks identification

In a second phase the constraints of the multi-energy networks are integrated using power flow simulation tool to characterize the bottlenecks and identify the retrofitting actions based on the definition of extreme operating conditions [4]. The constraints required to debottleneck the energy system are added in order to end-up with the generation of pertinent design scenarios.

2.3 Final design validated by co-simulation

To end-up with the final design, the proper operation of the precise design is validated with a co-simulation platform such as the obvious node Link co-simulator (onbl) [5].

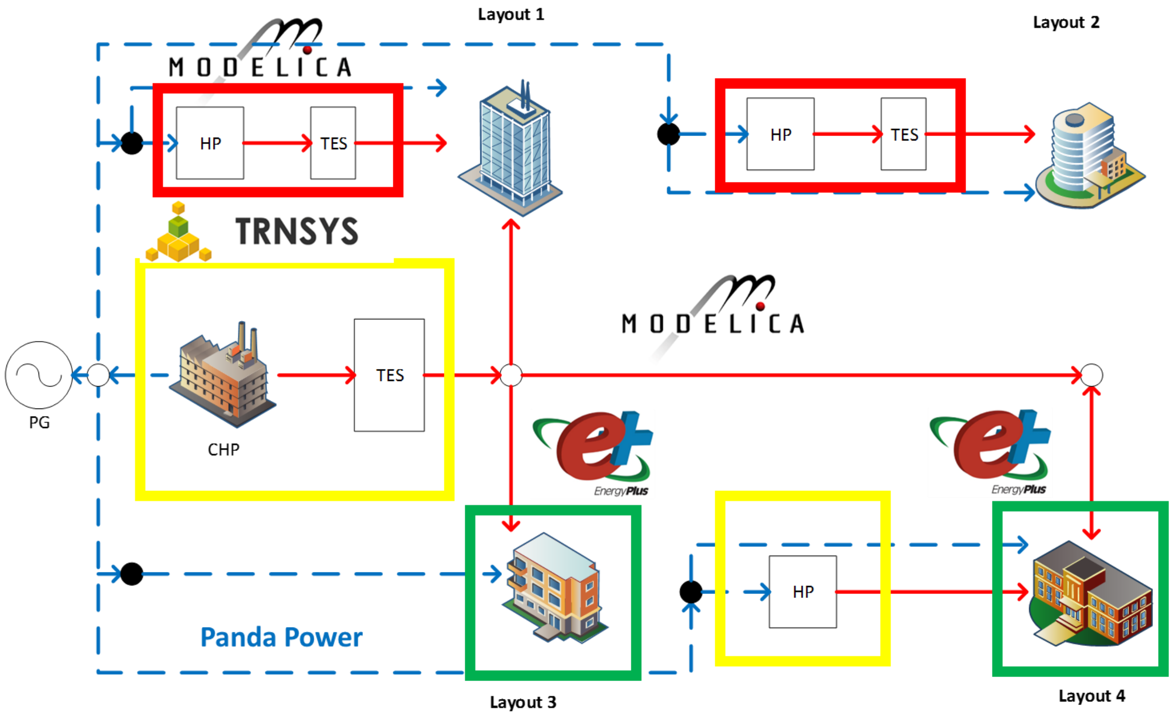

Figure 4: Co-simulation model linking and controlling simulation softwares (WP3 update, 2018)

3. Systematic generation of scenarios at building scale

This chapter describes the meta-model of the energy technologies in buildings derived from a multi-objective parametric optimization approach applied to a mixed integer linear problem (MILP) model which evaluates simultaneously the design and optimal operation of building energy systems [16].

3.1 Data reduction

In order to limit the computational effort related to presented problem formulation, the time dependent input profiles are clustered into 8 typical operating periods using a k-medoids classification method, hence reducing the problem size from $20^{\text{years}} \times 8760^{\text{hours}}$ to $8 \times 24^{\text{hours}}$. A further classification into a reduced set of typical building's energy profiles allows to reduce the number of profiles even more.

Spatial data reduction

Spatial data reduction aims at identifying typical geographical regions with identical climatic conditions. The applied approach described in [16] uses the k-medoids technique which provides more robust results than the commonly applied k-means technique [17].The cluster centres are defined from the initial data set based on the smallest sum of squared distances within each cluster.

The data set includes the number of heating (HDD) and cooling (CDD) degree days as well as the annual global horizontal irradiance (GHI) of a reference year (DRY) profile with hourly resolution. The annual cyclicity of the former climatic states supports the assumption of considering the weather data as constant over the entire equipment lifetime, hence decreasing the temporal simulation scope from about $20^{\text{years}} \times 8760^{\text{hours}}$ to $1^{\text{years}} \times 8760^{\text{hours}}$ time steps. The definitions of these parameters are expressed in equations (1)–(3) for each observation (i), where the index (d) represents a day and $\bar{T}^{amb}$ the mean daily ambient temperature.

$$HDD_i = \sum_{d=1}^{365} \left(18 - \bar{T}_{i,d}^{amb}\right) \qquad \forall \bar{T}_{i,d}^{amb} \leq 15 \tag{1}$$

$$CDD_i = \sum_{d=1}^{365} \left(\bar{T}_{i,d}^{amb} - 18\right) \qquad \forall \bar{T}_{i,d}^{amb} \geq 18.3 \tag{2}$$

$$GHI_i = \sum_{d=1}^{365} GHI_{i,d} \tag{3}$$

To guarantee a reliable representation of the original data by the reduced data space, a minimum acceptable number of clusters are defined on the basis of two quality indicators:

- The error in load duration curve (ELDC) indicating the global standard deviation of the original and clustered load curves;
- The mean profile deviation evaluating the difference between the observations and their representative cluster medoid.

The spatial cluster layout resulting from the application of the method at the communal scale in Switzerland is illustrated in Figure 5.

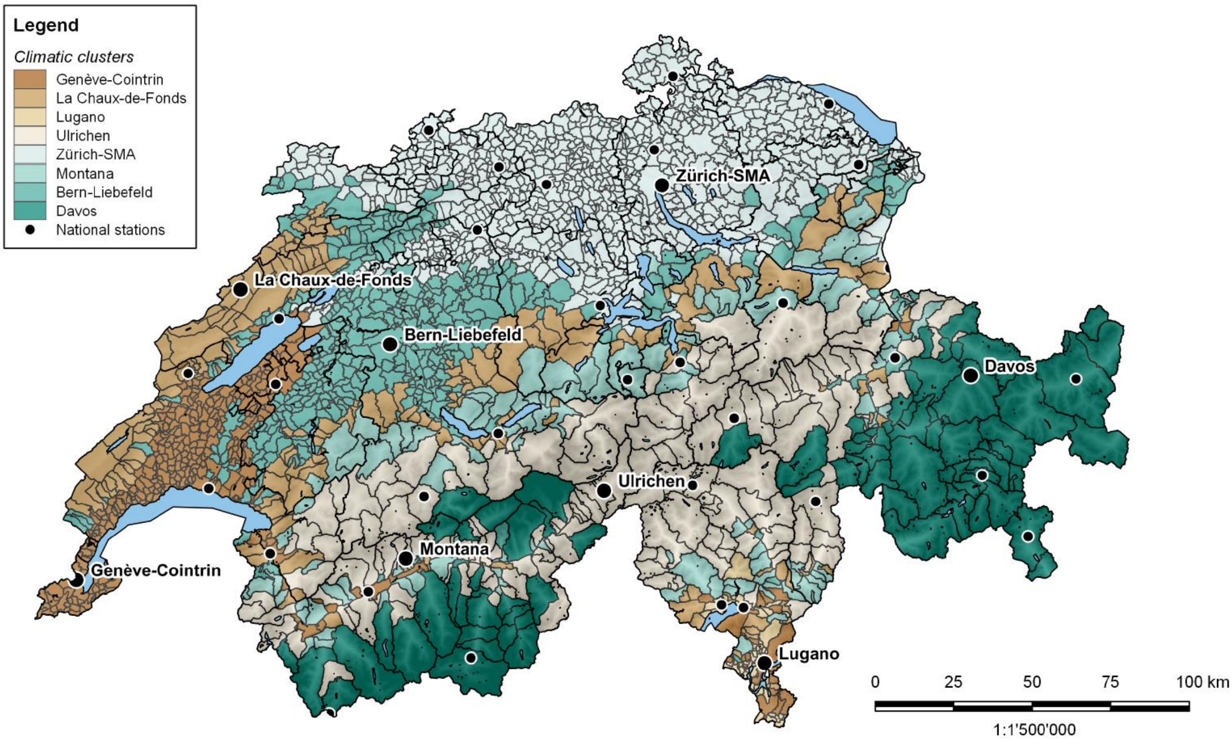

Figure 5: Typical climatic zones in Switzerland [18]

Temporal data reduction

In addition to the spatial dimension reduction, a second k-medoids clustering method is performed to decrease the temporal input data of the problem from 8760^{hours} hourly DRY profile to 6 to 12 × 24^{hours} typical operating periods with, in addition, 2 extreme periods to reflect peak demand hours. While similar performance indicators have been used to define the best partition number, solely two independent variables have been used: the daily ambient temperature and the global solar irradiance. Further information on the applied approach are given in [19] and [20]. Table 2 provides the selected days and annual frequency of occurrence which allow, as an initial approach, to extract the clustered load curves of the Lemanic arc from the original DRY profiles.

Table 2: Temporal cluster centers and occurrence the Lemanic zone in Switzerland [16]

Station		DRY Indexes							
Geneva-Cointrin	days	264	59	222	72	206	7	254	169
	freq.	54	46	17	49	52	68	49	30

Figure 6 represents the original DRY profiles of both attributes in addition of the load duration curves of both the original data and the respective typical days. As observed, the latter graph provides a good visual validation of the selected clusters [19], [16].

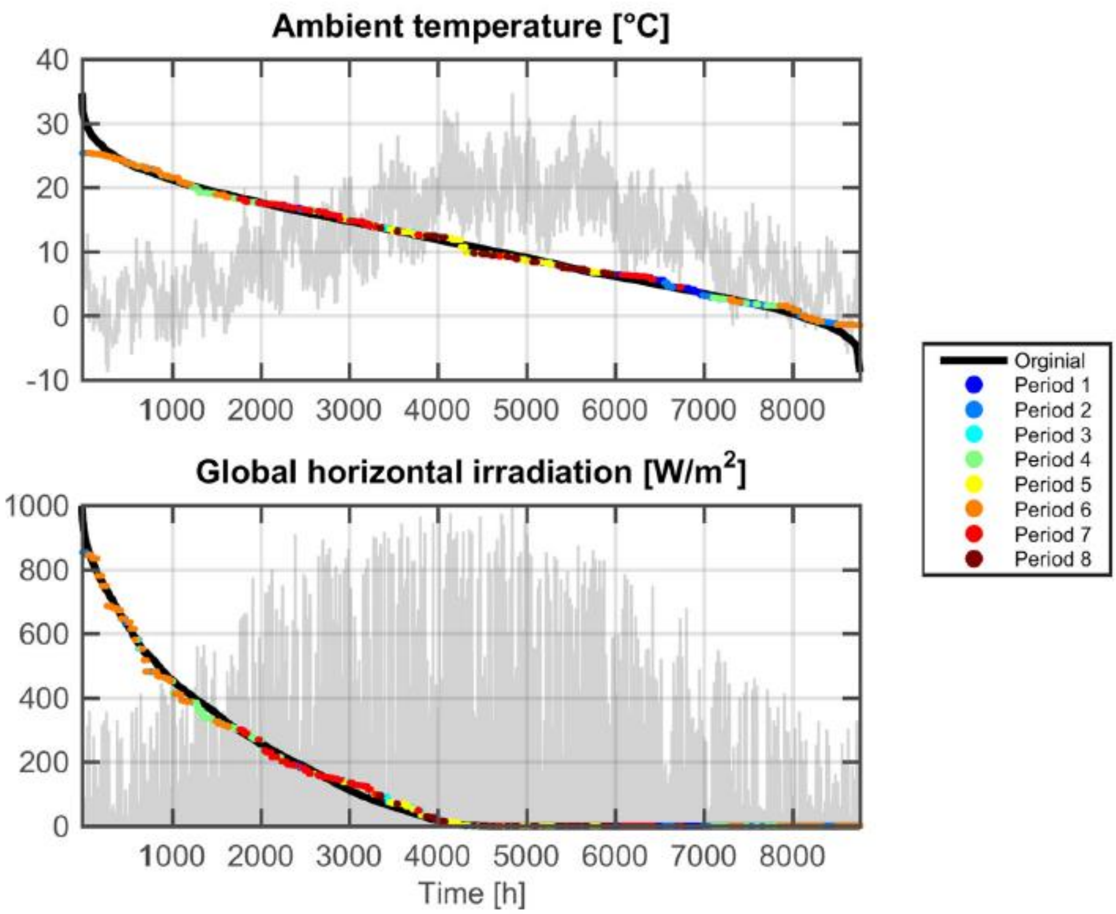

Figure 6: Ambient temperature and solar irradiation DRY load duration curves (black) and profiles (gray) of Geneva-Cointrin represented by 8 typical periods (colored) [16]

Typological data reduction

A further spatio-temporal classification step can be performed at the district level. A district might indeed be expressed as a collection of typical service demand profiles with a given probability of occurrence. Therefore, the temporal data reduction method is applied by considering height specific demand profiles for each urban area:

i. annual uncontrollable electricity;
ii. domestic hot water;
iii. internal heat loads;
iv. available solar potential;
v. space heating and
vi. space cooling energy signature;
vii. diurnal and
viii. nocturnal utilization hours.

This classification into a reduced set of typical energy profiles for buildings allows to reduce the number of profiles by four with errors of less than 10% [2], which remains within an acceptable range of tolerance.

3.2 Building energy system (BES) model

The modelling framework relies on MILP techniques to describe both the continuous (e.g. output modulation) and logical (e.g. start-up) behaviour of the devices. An overview of the latter is illustrated in Figure 7; it comprises an air-water heat pump as well as electric auxiliary heaters to satisfy the different heating requirements. Energy is stored in either stationary batteries, the domestic hot water and buffer tanks or the building envelope. Photovoltaic and solar collector panels act as renewable energy sources, the latter being only connected to the domestic hot water tank (HWT) in regard to the strong seasonal disparity of generation potential and space heating demand.

The different energy systems are finally interconnected through the main energy distribution networks: the natural gas, electricity and fresh water grid. Although the figure solely illustrates an air–water heat pump as primary thermal conversion unit, a cogeneration heat plant (CHP) device or a combination of multiple technologies might also be selected by the solver. To propose future, efficient energy systems to the different stakeholders, solely solid oxide (SOFC), and low temperature proton exchange membrane fuel cells (LPEM) are considered as CHP units in the following structure. In addition, it is worth noting that the final hydraulic layout (including, e.g., pumps, by-passes, three-way valves) of the designed BES may be implemented differently, according to the selected solution. Further details on the optimization problem formulation and input data are reported in [18].

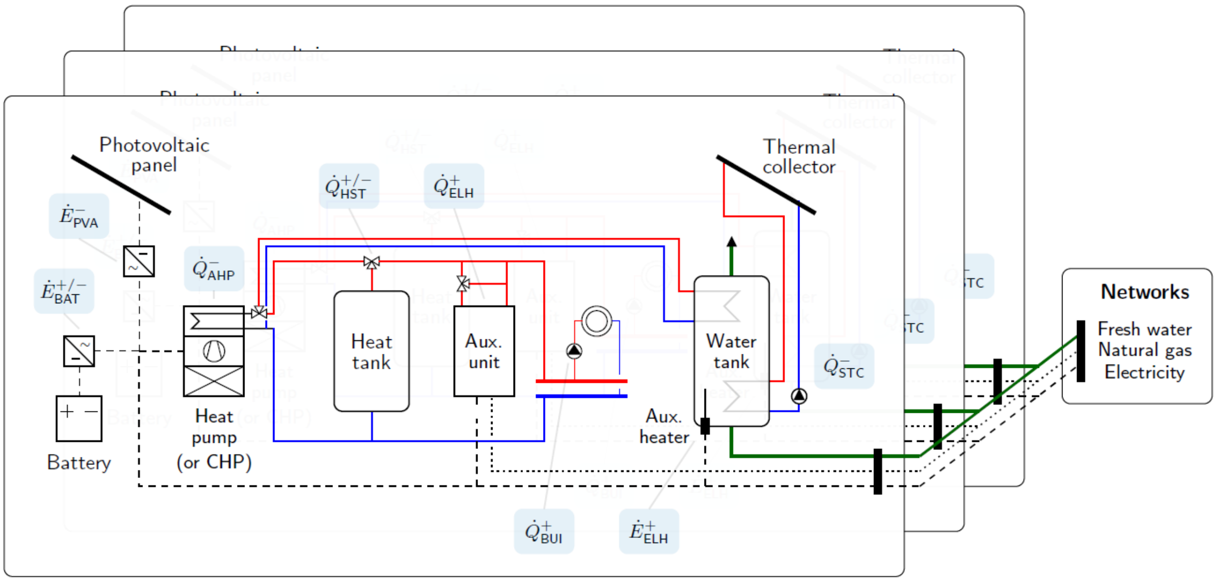

Figure 7: Building energy system structure and the respective control variables (blue) [2]

Sets

The sets and their respective indices used in the MILP formulation are reported in Table 3.

Table 3: List of defined sets with description

Set	Index	Increment	Cyclic	Description
P	p	d_p	No	Period (day)
T	t	d_t	Yes	Time (hour)
K	k		No	Temperature level
U	u			Utility types
B	b			Building

Figure 8 illustrates the building energy system structure. Hydraulic connections, valves and circulation pumps are not considered in the model.

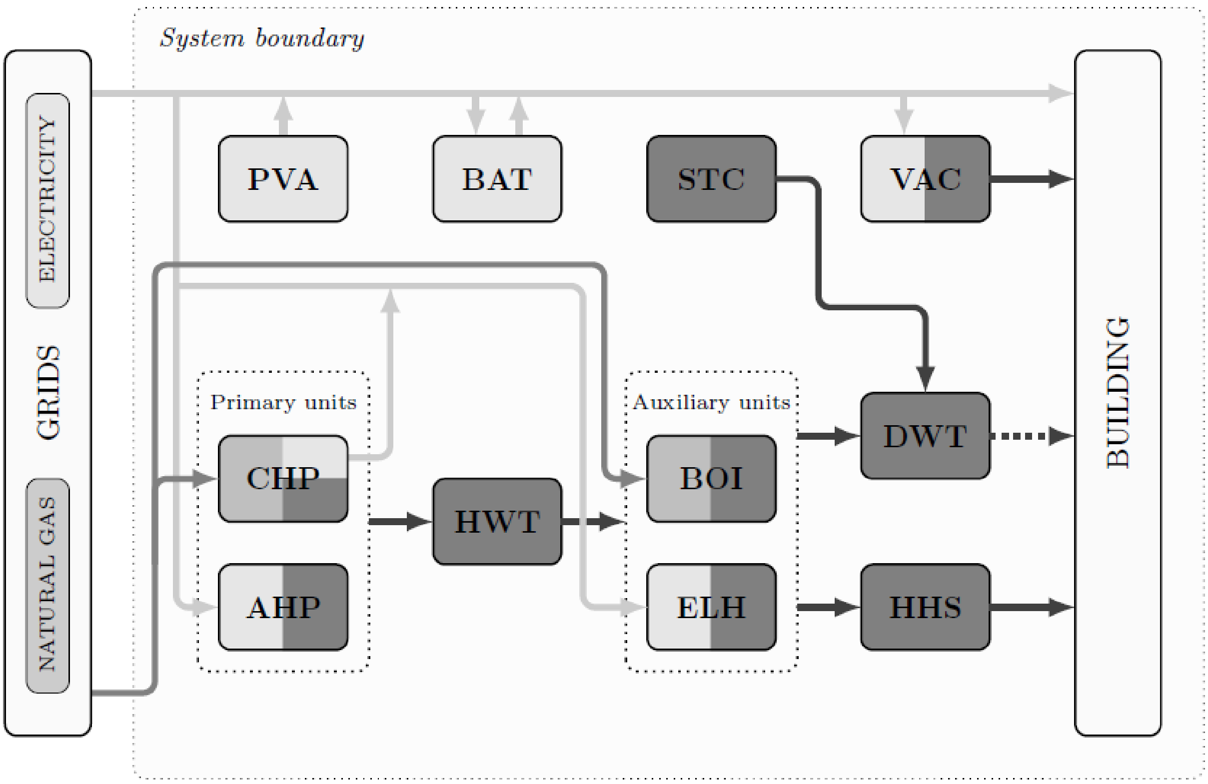

Figure 8: Energy system structure: electricity flows (light grey), natural gas flows (grey), heating/cooling flows (dark grey) [16]

Model input and output

When measurements are not available, the different domestic service demands of each dwelling are estimated using both statistical and normalized data. Indeed, considering the approach developed by [21], space heating demands are determined through the means of the energy signature definition while the remaining service requirements (domestic hot water preparation and electricity) are evaluated using standards of the Swiss society of engineers and architects [22]. Figure 9 depicts standardized daily profiles for a single family house, an apartment block and an office building.

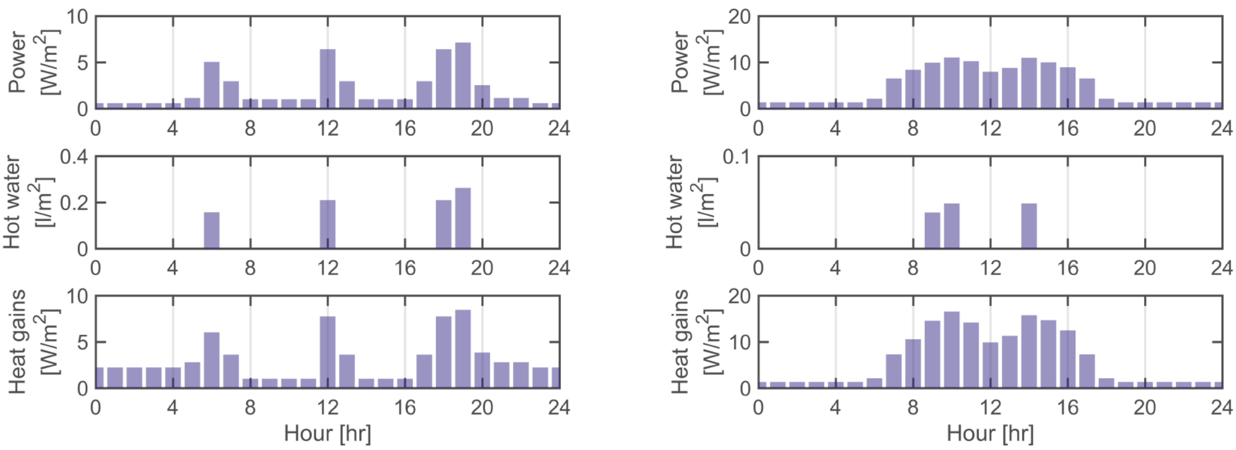

Figure 9: Service demand profiles of a single family house (left) and an office building (right) [22]

The input for the BES model are detailed in Table 4.

Table 4: Building energy system input for the systematic generation of alternative scenario of building energy system

Field	Description	Unit
Objective and Limits	Objective Function (OPEX, CAPEX)	[-]
	Upper limit for the specific annualized investment	[CHF/(m2·y)]
Time data	Typical operating days number (1-365)	[-]
	Frequency of the typical days	[d/y]
	Extreme operating periods	[-]
Electric Profiles	Uncontrollable load profiles	[kW]
	Grid multiple factor (GM)	≥1
Building data	Grid parameter, transformer responsible for house connection	[-]
	Share of useful roof	[-]
	Solar gain (fraction of House area)	[-]
	Reference indoor temperature	[°C]
	Specific heat transfer coefficient of the building	[kW/K·m^2]
	Type and period of construction/renovation	[-]
	Specific electric needs	[W/m^2]
	Reference Energetic Area or heated surface	[m^2]
	Sizing return temperature of the hydronic heating system (HSS)	[°C]
	Sizing supply temperature of the hydronic heating system (HSS)	[°C]
	Number of inhabitant	[cap]
	Specific domestic hot water demand	[W/m2]
	Building type	[-]
	Unique identifier	[-]
	Number of floors (stories) of building	[-]
	Specific heat capacity of the building	[Wh/K·m^2]
Equipment	Possible presence of equipment in building (heat pumps, boiler, electrical heater, cogeneration engine, PV, solar thermal collector, domestic hot water tank, hot water tank for space heating and battery)	[0, 1]

The main output of the model are the sizes and hourly profile of operation of the devices and the corresponding emissions, operating and investments costs. Additionally, the detailed analysis is complemented by plotting the aggregated feeder power profile as well as the global energy system design scenarios.

Formulation of the multi-objective optimisation problem

The optimal integration of the building energy technologies is formulated as a multi-objective optimization problem based on a MILP formulation with the annual building operating expenses (OPEX) as the main objective. The OPEX comprise both the natural gas and power grid exchanges. The former are defined in equation (4) where (op) refers to the grid energy tariffs, (E) to the electrical power flows, (H) to the chemical–natural gas–power flows, (d) to the indexed time step duration, and (Σ) to the set of decision variables reported in [18].

$$\min_{\Sigma} \sum_{p=1}^{P} \sum_{t=1}^{T} \left(\dot{Q}^{+}_{grid,p,t} \cdot op^{th,+}_{p,t} + \dot{E}^{+}_{grid,p,t} \cdot op^{el,+}_{p,t} - \dot{E}^{-}_{grid,p,t} \cdot op^{el,-}_{p,t} + \dot{H}^{+}_{grid,p,t} \cdot op^{ng,+}_{p,t} \right) \cdot d_p \cdot d_t \tag{4}$$

The second objective, formulated as a parametric ϵ-constraint in the optimization problem, is the present capital expenses related to the different unit purchases over the project horizon (N). In equation (5), ($I_{1,u}$) and ($I_{2,u}$) denote the linear cost function parameters, (y_u) the unit existence while (f_u) is the device sizing variable. In addition, (N_u) refers to the unit lifetime, (r) the project interest rate and (rep_u) to the number of unit replacements over the project horizon.

$$\sum_{u=1}^{U} \left(I_{1,u} \cdot y_u + I_{2,u} \cdot f_u \right) + \sum_{u=1}^{U} \sum_{n=1}^{rep_{u,N}} \frac{1}{(1+r)^{n \cdot N_u}} \cdot \left(I_{1,u} \cdot y_u + I_{2,u} \cdot f_u \right) \leq \epsilon_I \tag{5}$$

Finally, a third objective function—implemented as an ϵ-constraint—is used to represent the power network constraint: the grid multiple (GM). As detailed in equation (6), this parameter limits the building power profile peaks ($\dot{E}_{grid}$) with respect to the daily average demand and thus decreases the consequent stress on the distribution network from strong demand/supply surges. For the sake of readability, the total period duration is denoted by (n_t).

$$\frac{\left(\dot{E}^{+}_{grid,p,t} - \dot{E}^{-}_{grid,p,t} \right)}{\frac{1}{n_t} \sum_{t=1}^{T} \left(\dot{E}^{+}_{grid,p,t} - \dot{E}^{-}_{grid,p,t} \right)} \leq \varepsilon_{GM} \tag{6}$$

Heat Cascade

The heat cascade balances the system heat loads while satisfy the second law of thermodynamics. Equation (7) thus defines the thermal energy balance of each temperature interval k where ($\dot{Q}^{-}_{u_h,k}$) represents the released heat of utility (u_h), ($\dot{Q}^{+}_{u_c,k}$) represents the heat demand of utility (u_c), and ($\dot{R}_k$) the residual heat cascaded to next interval (k+1). In addition, no heat is cascaded at the first and last intervals to ensure a closed thermal energy balance.

$$\dot{R}_{k,p,t} - \dot{R}_{k+1,p,t} = \sum_{u_h=1}^{U} \dot{Q}^{-}_{u_h,k,p,t} - \sum_{u_c=1}^{U} \dot{Q}^{+}_{u_c,k,p,t} \qquad \forall p \in \boldsymbol{P}, t \in \boldsymbol{T}, k \in \boldsymbol{K} \tag{7}$$

$$\dot{R}_{1,p,t} = \dot{R}_{n_k+1,p,t} = 0$$

Energy Balances

The electrical ($\dot{E}$) and natural gas energy ($\dot{H}$) balances are defined in equation (8) where ($\dot{E}_b^-$) refers to the building uncontrollable load profile.

$$\begin{aligned} \dot{E}^+_{grid,p,t} + \sum_{u=1}^{U} \dot{E}^+_{u,p,t} &= \dot{E}^-_{grid,p,t} + \sum_{u=1}^{U} \dot{E}^-_{u,p,t} + \dot{E}^-_{b,p,t} \\ \dot{H}^+_{grid,p,t} &= \sum_{u=1}^{U} \dot{H}^-_{u,p,t} \end{aligned} \qquad \forall p \in \boldsymbol{P}, t \in \boldsymbol{T} \qquad (8)$$

Cyclic Conditions

To prevent any energy accumulation between the different independent operating periods (p), cyclic constraints of equation (9) enforce all system states to return to their initial value at the end of each control horizon (n_t). The latter constraints target the building indoor temperature (T_b) as well as the thermal (Q) and electrical energy (E) stored in the respective storage units. The typical days (p) represent indeed different operating conditions with a given probability of occurrence during the system lifetime. Equation (9) is therefore included in the problem formulation to avoid any energy bias.

$$\begin{aligned} T_{b,p,1} &= T_{b,p,n_t} \\ Q_{u,p,1} &= Q_{u,p,n_t} \\ E_{u,p,1} &= E_{u,p,n_t} \end{aligned} \qquad \forall p \in \boldsymbol{P}, u \in \boldsymbol{U} \qquad (9)$$

Unit Sizes

The unit existence (y_u) and logical state on/off ($y_{u,p,t}$) are expressed in equation (10) where (F_u^{min}) and (F_u^{max}) describe the device minimal and maximal sizing values.

$$\begin{aligned} y_u \cdot F_u^{min} \leq f_u &\leq y_u \cdot F_u^{max} \\ y_{u,p,t} &\leq y_u \end{aligned} \qquad \forall u \in \boldsymbol{U} \qquad (10)$$

3.3 Meta-model

The meta-model is composed of the set of optimal Pareto points resulting from the resolution of the BES model (§3.2). The design and corresponding optimal operation profiles are given as a function of:

i. the total investments costs (CAPEX);
ii. the thermal network energy distribution cost;
iii. the grid multiplication factor (GM).

The level of granularity of the model depends on the number of predefined points defined by the number of epsilon-constraint from Equation (5, 6) and network distribution cost parameterization. An example of meta-model of 16 scenarios (8 investments steps, two network distribution cost and a unique, unlimited GM factor) is shown in Figure 10.

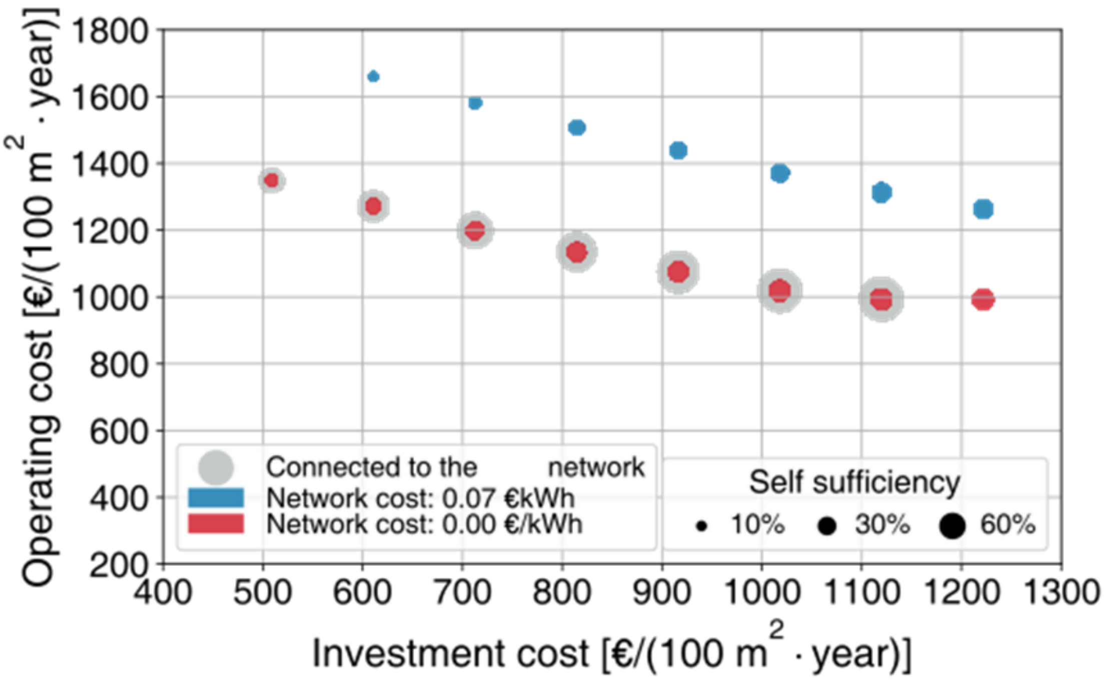

Figure 10: A meta-model (optimal scenarios) as a function of the investment for existing buildings [3]

4. Systematic generation of scenarios at district scale

A method to generate decentralized energy technology scenario at building scale, with the possibility to connect to a district heating network, has been presented in Chapter 3. Chapter 4 presents the integration, at district scale, of multiple decentralized building's energy technologies with centralized plant, such as cogeneration engine, central heat pump, geothermal plant, waste heat recovery or waste heat treatment plant.

4.1 Multi-objective optimisation model

To solve this problem process energy integration techniques is used at an upper level to integrate energy technologies considering temperatures constraints, mass and energy balance. The meta-models of BES, generated at a lower level for each buildings of the district, are integrated as energy technologies in the same manner as centralized plant (Figure 11).

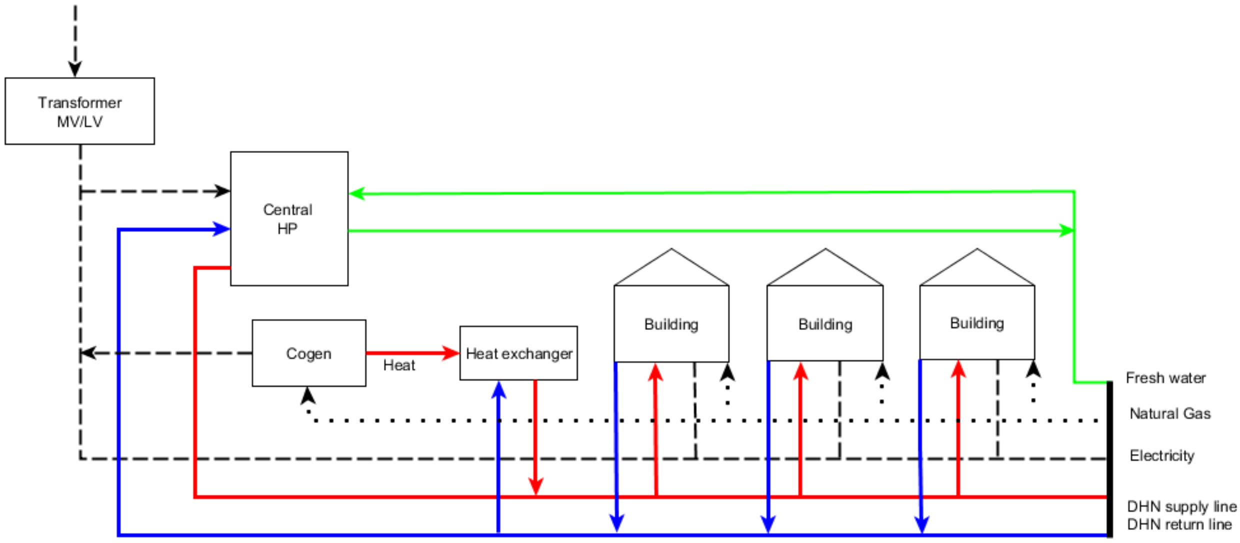

Figure 11: Energy technologies superstructure in OSMOSE

The solver of OSMOSELua minimize both the operating and investment costs of Equation (11) and (5) to select the optimal operation and investment strategy for all energy technology units (u), comprising the central plants and the buildings energy systems.

$$\min_{y_{u},f_{u}} \sum_{u=1}^{U}\sum_{p=1}^{P}\sum_{t=1}^{T}\left(\left(y_{u,p,t}\cdot op_{u,p,t}^{+}+f_{u,p,t}\cdot op_{u,p,t}^{+}\right)+\dot{E}_{grid,p,t}^{+}\cdot op_{p,t}^{el,+}-\dot{E}_{grid,p,t}^{-}\cdot op_{p,t}^{el,-}\right)\cdot d_{p}\cdot d_{t} \quad (11)$$

The solving procedure leads to the generation of CAPEX-OPEX Pareto fronts which represents alternatives scenario for the DES. At the solving stage in case of the DHC network is not existing, the DHC distribution cost is not unknown as the connection of each building to the network is laid as an open option. A Pareto front is therefore generated for a given number of predefined DHC distribution cost. For example, Figure 12 presents height Pareto fronts of fourteen points corresponding to alternative scenarios for DES design. Figure 13 shows the corresponding mix of energy technologies selected for each scenario 1 to 14.

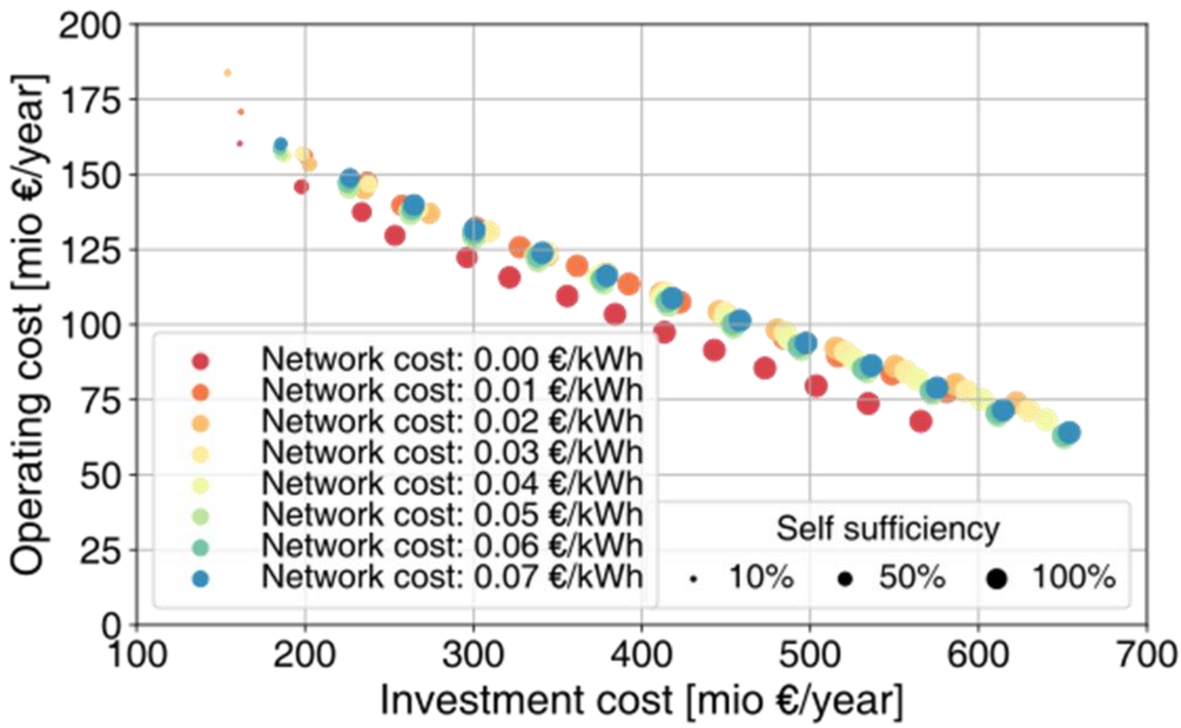

Figure 12: Pareto front at district sacle for various DHN distribution cost assumptions [3]

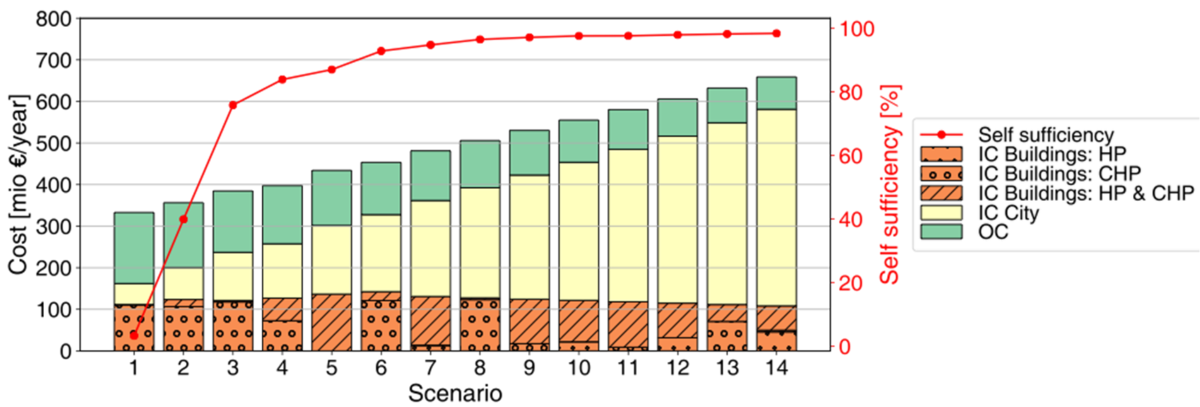

Figure 13: Mix of energy technologies at district scale for each scenario [3]

4.2 Heat distribution cost

The investment cost of the DHC network is not taken in to account at building scale. However, it is computed at district scale as soon as the number of connected building has been identified by the solver. To speed up the computation, the cost of the infrastructure is computed without using a routing algorithm, but with an idealised grid pattern (Figure 14) and a factor of experience (K) linking real and idealized network topology.

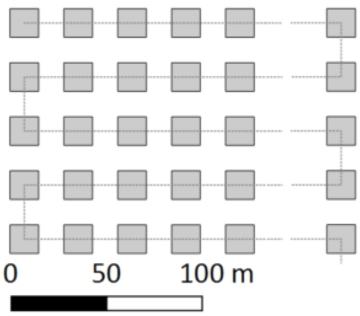

Figure 14: Idealized grid pattern

The heat distribution cost of the networks is calculated using the formulation of [7]. First, the length of the network (L^{DHN}) is calculated based on the number of buildings (n_b), the land surface area (A_l) and a correlation coefficient (K) [21]:

$$L^{DHN} = 2 \cdot (n_b - 1) \cdot K \cdot \sqrt{\frac{A_l}{n_b}} \quad (12)$$

And for each segment (between each two buildings):

$$L_k^{DHN} = \frac{L^{DHN}}{n_b} \quad (13)$$

Next, the mass flow in the pipes is computed using the maximum heat flow in the pipe ($\dot{Q}^{DHN}$) and the specific heat flows ($q^{DHN} = c_{p,water} \cdot \Delta T^{DHN}$):

$$\dot{m}_{max}^{DHN} = \frac{\dot{Q}^{DHN}}{q^{DHN}} \quad (14)$$

And for each segment (k):

$$\dot{m}_j^{DHN} = \frac{\dot{Q}^{DHN} \cdot (n_b - j + 1)}{n_b \cdot q^{DHN}} \quad (15)$$

Then, the diameter of the pipes (d^{DHN}) is calculated using the mass flow ($\dot{m}^{DHN}$), the sizing velocity of the fluids (v) and the density of the fluids (ρ):

$$d_j^{DHN} = \sqrt{\frac{4 \cdot \dot{m}_j^{DHN}}{\pi \cdot v \cdot \rho}} \quad (16)$$

Finally, the investment cost (IC^{DHN}) of the networks is computed by summing up the different segments, using the cost coefficients (c_1) and (c_2) an interest rate i = 5% and a lifetime N = 60 years [21]:

$$\tau^{DHN} = \frac{(i+1)^N - 1}{i \cdot (i+1)^N} \quad (17)$$

$$IC^{DHN} = \sum_{j=1}^{n-1} \frac{L_k^{DHN}(c_1 \cdot d_j^{DHN} + c_2)}{\tau^{DHN}} \tag{18}$$

Table 5: Network cost parameters

Parameter	Value (water network)	Unit
$\boldsymbol{K}$	0.23	[-]
$\boldsymbol{v}$	3	[m2/s]
$\boldsymbol{\rho}$	1000	[kg/m3]
$\boldsymbol{c_1}$	5670	[e/m2]
$\boldsymbol{c_2}$	613	[e]
$\boldsymbol{i}$	0.06	[-]
$\boldsymbol{t}$	60	[-]

5. Outlook and Conclusions

The proposed approach combines energy integration techniques to generate wide ranges of alternatives for preliminary design of district energy systems (DES) and co-simulation approach towards the selection of final design.

The generation scenario at district scale follows a two-level approach: the definition of meta-models for the decentralized energy system (BES) at building level followed by their integration with the centralized plants at district scale.

At building scale, the portfolio of competing technologies is composed of gas boiler, cogeneration engine, air-water heat pump or heat pump connected to the district heating, district heating, separate thermal storage for space heating and hot water, photovoltaic panels and battery.

At district scale the scenarios are selected using multi-objective optimisation with operating cost (OPEX) and investment cost (CAPEX) as objective. This allows to propose optimal sizes and allocations for the centralized (cogeneration plant and district heating heat pump) and decentralised energy technologies as a function of the investment budget.

The method has been validated, phase by phase, using small-scale case studies. As further work (Task 4.2), it is going to be applied on the full-scale test cases. Moreover, a geo-location indicator is going to be introduced for the energy technologies in the multi-objective optimisation procedure in order to favour spatial homogeneity in the territorial energy concept.

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