Multi-objectives, multi-Period optimization of district energy systems: III-Distribution networks

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Abstract

A systematic procedure including process design and integration techniques for designing and operating energy distribution networks, and for transportation of resources is presented in this paper. In the developed model a simultaneous multi-objectives and multi-period optimization is principally investigated. In addition to optimize the transportation of resources/products, the proposed method helps decision makers to decide; which type and size of poly-generation technologies, centralized or decentralized, are best suited for the district, where in the district shall the equipment be located (geographically), how the services should be distributed, and what are the optimal flow, supply and return temperatures of the distribution networks. The design and the extension of distribution networks and transportation of resources, based on the geographical information system (GIS), are the novelties of the pressnt work.

Keywords: Distribution networks, Typical operating periods, District energy systems, Mixed Integer Linear Programming, Evolutionary algorithm, Multi-objectives optimization, Geographical information system (GIS), CO_2 mitigation

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1. Introduction

In the perspective of increasing the share of renewable energies, global warming mitigation and with respect to the issue of sustainable energy development, a district energy system, joined with poly-generation technologies, has been considered as a promising option [1].

In the district energy system there are three main challenges; on environmental aspect, on energy efficiency and on economic aspect. The complexity consists in supplying clean energy, consuming fewer fossil resources and finding appropriate solutions to reduce the emissions while also satisfying the energy requirement. Therefore, a systematic procedure is needed to optimize the design and the operation of the district energy system together with optimizing the size and the layout of physical distribution networks and logistics which is taking into account environmental burdens and costs simultaneously.

Multiple research studies have been carried out for simulation and optimization of individual conversion technologies. It is referred to [2] for a detailed review. The role of design optimization techniques in power generation is also reviewed by [3]. Centralized and decentralized technologies are relatively well understood today but the supply side is not the only elements of district energy systems. To enhance a sustainable energy system a number of issues need to be addressed and optimized simultaneously; such as distribution networks layout, costs, fuel availability, renewable sources, environmental impacts and energy demand fluctuation.

Focusing on purely economic indicators for designing energy systems, has already been under taken by the majority of optimization studies. E. Cardona [4] applied mono-objective linear programing with boundary constraints related to the secondary objectives for energy saving in airports. D.Ziher [5] also used the same approach for analyzing the tri-generation system in a hospital, while P.Arcuri et al. [6] applied a mixed integer programming model with ϵ constraint. M.Casisi et al. [7] proposed a mixed integer programming model to optimize a distributed cogeneration system with a district heating network. A mixed integer linear programming (MILP) for optimizing the preliminary design of combined heat, cooling and power systems with thermal storage is presented by M.A.Lozano et al [8]. Selection and sizing of technologies in a poly-generation scheme are investigated with nonlinear programing [9, 10]. Haesen et al. [11] introduced a methodology for long-term planning of district energy systems (DES) placement with multi objectives approach.

Multi-objectives optimization of energy systems can be achieved through diverse optimization techniques, such as genetic and evolutionary algorithms and linear or non-linear programming [12, 13]. However, these optimizers frequently face questions on their performances [14]. A multi-objectives optimization for designing of a small-scale distributed CCHP system has been performed by [15] in which a genetic algorithm has been applied to find the set of Pareto optimal solutions. A multi-objectives optimization model based on the trade-off curve for analyzing the optimal operating strategy of a district energy system is applied by [16]. There the trade-off analysis is performed between the pure environmental optimization and the pure economic optimization, rather than simultaneous optimization of both objectives. A multi-objectives optimization model based on the harmony search algorithm (HS) is presented [17] to design the low-emissions and energy-efficient residential buildings. This algorithm uses stochastic random searches and performs well for global searching, however, since it does not use gradient information it may take a relatively long time to converge to a local optimal.

Papoulias and Grossmann [18] have studied the network configuration of energy systems and have developed a tool for decision makers to design the layout of the networks. Their work does not take into account the temperature levels at which the energy services have to be delivered. Moreover, Söderman and Ahtila [19] develop a mixed integer linear programming model with mono economic objective function to select the location and capacity of the cooling and heating conversion technologies, and to route the distribution pipelines to individual consumers. They present an optimization model for the strategic design of integrated urban energy systems without taking into account the environmental burdens.

A multi-objectives, multi-period optimization model including process design and energy integration techniques is described in [20, 21]. However, the optimization of the transportation of resources and the layout of distribution networks were not included. The model is extended in the present work by optimizing the logistics of resources/products, and by optimizing the pipeline temperatures and layout between consumers and suppliers.

Finally, the potential and the flexibility of the proposed model are demonstrated by means of a case study.

2. Multi-objectives optimization of a district energy system: Methodology

A systematic approach has been developed for sizing and operating a district energy system [20, 21]. The developed methodology combines conversion technologies modeling using established flowsheeting tools, energy integration, economic evaluation and environmental impact assessment in a multi-objectives optimization framework following the approach presented by [22]. It has the aim of obtaining a set of optimal district energy system configurations, and can be split up into three principle phases;

- **Structuring phase** in which required data will be collected and structured.
- **Optimization phase** in which a complex non-linear problem to generate systematically a multitude of possible solutions, placed on a Pareto frontier, will be solved.
- **Post-Processing phase** in which, Pareto frontier will be studied in detail in order to propose an optimal solution.

Through a MATLAB-language based platform (MathWorks Inc.), structured data is transferred between the different phases. The main features of the methodology are summarized in Figure 1.

2.1. Structuring phase

Required data for solving the optimization step will be collected and structured in the structuring phase. These principally include, the available energy sources, the energy consumption profiles, simulation model of available and alternative conversion systems and individual backup technologies including their technical and costs data, and the geographical information of a district area. These information can be structured in the form of the database.

The demand profile is one of the main input data. It is characterized by power requirement and corresponding temperatures based on the hourly profile. However, such a detailed description of the demand profile requires excessive computational resources for solving an optimization model. One way to reduce the size of the optimization model is to represent the yearly profile using a limited set of typical operating periods. A clustering method is developed [23] to select the typical periods.

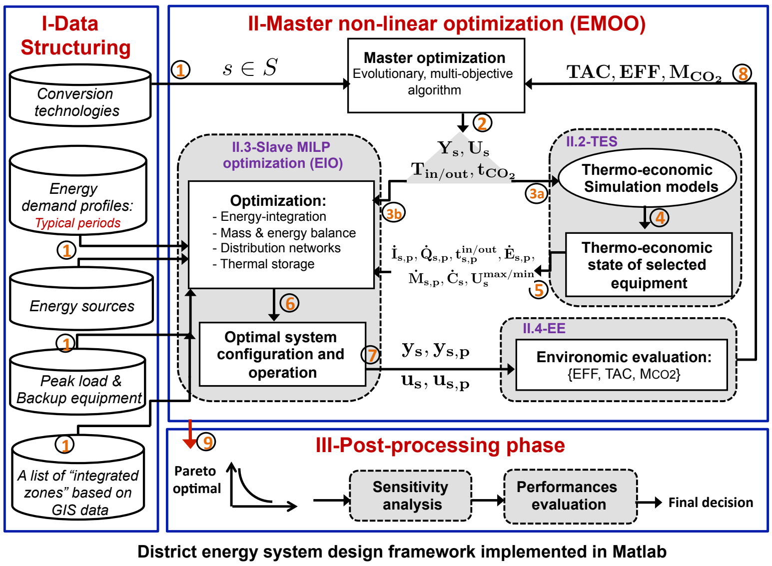

Figure 1: Illustration of the developed methodology for district energy systems design and operation optimization

2.2. Nonlinear optimization phase

In order to optimize the size and the operating schedule of the district energy system, with regard to energetic, economic and environmental indicators, multi-objectives optimization techniques are applied. The optimization model includes continuous (i.e. unit configuration and operation) as well as integer type variables (unit existence). Consequently, it belongs to the class of the Multi-objectives Mixed Integer Non-Linear Programming model (MMINLP). In the present work, evolutionary and conventional algorithms, described in [13, 22], are chosen among all developed techniques [24] to solve the MMINLP model. The use of the evolutionary algorithm makes the approach less sensitive to non-convergence problems.

The basic concept of the developed model is the decomposition of the optimization phase into four major steps [20], **Master optimization**, **Thermo-Economic simulation** (TES), **Slave optimization** (EIO) and **Thermo-environomic evaluation** (EE) (Figure 1).

2.2.1. Master optimization

The objective functions of the master optimization (Eq.1) are; the maximization of the system's efficiency (EFF), and minimization of both the overall CO_2 emissions (M_{CO_2}) and the total annual costs (TAC) including investment and operating expenses (Sec 2.2.5).

Decision variables in the master optimization are summarized in Table 1 and include: binary variables ($\mathbf{Y}_s$) for the choice of the district energy conversion technologies ($s \in S$) and the connection to the heating distribution networks, continuous variables for sizing conversion technologies ($\mathbf{U}_s$) with feasible ranges between minimum (F_s^{min}) and maximum (F_s^{max}) sizes, resource availability ($\mathbf{B}_f$), related parameters of various technologies, the CO_2 emissions weighting factor ($\mathbf{t_{CO_2}}$) which can be replaced by other type of environmental impacts, the design flow velocity (ν [m/s]) and the supply and return temperatures of the heating and the cooling distribution networks ($\mathbf{T}_{in}^{h/c}$ and $\mathbf{T}_{out}^{h/c}$). The ranges of continuous variables have been normalized to homogenize the ranges of decision variables and therefore ensure a better covering up of the search space [22].

$$\max_{\mathbf{U_s},\mathbf{Y_s}} \{\mathbf{EFF}\}, \quad \min_{\mathbf{U_s},\mathbf{Y_s}} \{\mathbf{TAC}, \quad \mathbf{M_{CO_2}}\} \tag{1}$$

subject to:

$$T'_{min} \leqslant \mathbf{T}_{in}^{h/c} \leqslant T'_{max}$$
$$T_{min} \leqslant \mathbf{T}_{out}^{h/c} \leqslant T_{max}$$
$$0 \leqslant \mathbf{t_{CO_2}} \leqslant Tax_{max}$$
$$F_s^{mins} \leqslant \mathbf{U}_s \leqslant F_s^{max} \qquad \forall s \in S$$
$$\mathbf{B}_f \leqslant b_f^{max} \qquad \forall f \in F$$
$$\mathbf{Y}_s \in \{0,1\} \qquad \forall s \in S$$
$$(\dot{\mathbf{I}}_{s,p}, \dot{\mathbf{Q}}_{s,p}, \dot{\mathbf{E}}_{s,p}, \dot{\mathbf{M}}_{s,p}, \mathbf{C}_s, \mathbf{t}_{s,p}^{in/out}, \mathbf{U}_s^{max/min}) = \mathbf{TES}(U_s, Y_s, T_{in}^{h/c}, T_{out}^{h/c}) \quad \forall s \in S$$
$$(\mathbf{u}_s, \mathbf{y}_s, \mathbf{u}_{s,p}, \mathbf{y}_{s,p}) = \mathbf{EIO}(t_{CO_2}, B_f, \dot{I}_{s,p}, t_{s,p}^{in/out}, T_{in/out}^{h/c}, \dot{Q}_{s,p}, \dot{E}_{s,p}, \dot{M}_{s,p}, C_s, U_s^{max/min})$$
$$(\mathbf{EFF}, \mathbf{TAC}, \mathbf{M_{CO_2}}) = \mathbf{EE}(u_s, y_s, u_{s,p}, y_{s,p})$$

The constraints of the master optimization include the thermo-economic simulation (TES) models of the district energy conversion technologies (Sec 2.2.2), the slave energy integration optimization (EIO) (Sec 2.2.4), as well as the environomic evaluation (EE) (Sec 2.2.5).

2.2.2. Thermo-Economic simulation (TES)

The district energy system contains several subsystems ($s \in S$) including; buildings ($b \in S$), conversion technologies, storage tanks ($s' \in S$) and heating/cooling distribution networks. Each subsystem is placed in a location ($g \in G$). As mentioned before, the type (Y_s), the size (U_s) and the related operating parameters of subsystems are decision variables whose values are fixed by the master optimization. Subsequently, in this step the thermodynamic and economic states of buildings and selected equipment are calculated by using thermo-economic simulation models (TES) and external flow-sheeting tools (Belsim Vali). The goal is to estimate the **linear** operating expenses ($\mathbf{C}_s$), emissions ($\dot{\mathbf{I}}_{s,p}$), inlet ($\dot{\mathbf{M}}^-_{s,p}$) and outlet ($\dot{\mathbf{M}}^+_{s,p}$) materials (i.e. water, products, waste and fuels in [kW] or [kg/s]), the feasible ranges of subsystem's utilization ($\mathbf{U}^{min}_s$, $\mathbf{U}^{max}_s$), the power ($\dot{\mathbf{E}}_{s,p}$), the heat load of the heat transfer requirement and the temperatures ($\dot{\mathbf{Q}}_{s,p}$, $\mathbf{t}^{in/out}_{s,p}$) in the reference, nominal and part loads conditions, and translate them into a set of **streams** (Figure 2 and Table 2). The idea is to structure the input data (expenses, emissions, power, material flows, and thermodynamic data) in an efficient way in the slave optimization model. For this purpose, three types of streams are defined;

1. Material ($\dot{M}$) streams to represent the inlet and outlet materials (i.e. water, products, waste, fuels) and the emissions of subsystem s,
2. Power ($\dot{E}$) streams for the electricity consumption and production,
3. Heat cascading ($\dot{Q}$) streams for presenting the temperatures and the enthalpy of heating/cooling requirements.

Streams are grouped into a set of **layers**. Layers are defined in order to classified the type of equations and constraints of the slave optimization model. The three types of layers are;

1. Local balancing layers (L_{bl}) for balancing the quantities of materials (i.e. water, products, waste, fuels) and power between subsystems in each location ($g \in G$), without any export/import to/from other locations or outside the system boundaries.
2. Global balancing layers (L_{bg}) for balancing the quantities of power and materials (i.e. water, products, waste, fuels) between subsystems inside and across locations ($g \in G$), with possibility of exporting/importing power and materials (i.e. water, products, waste, fuels) to/from outside the system boundaries.

3. Heat cascading layers (L_h) for heat exchange and heat recovery between subsystems by including the temperatures at which the heating and cooling requirements are needed.

In the local and the global balancing layers only the quantity is considered. However, in the heat cascading layers not only the quantity but also the quality of streams, in terms of temperatures, are defined. Since in the slave optimization the exchange between layers is not allowed, several layers can be defined in order to restrict the exchange between subsystems.

Presenting subsystems with respective streams and layers are the main input data in the slave linear optimization (MILP), therefore should be able to be treated linearly or piecewise linearly. Piecewise linearization techniques [25] are used to define non linear performances (i.e. costs, efficiency) as a set of linear segments.

Table 2 resumes the input data and variables of the thermo-economic simulation (TES) step.

2.2.3. Definition of ΔT_{min}

A heat exchanger enables the heat transfer from the hot stream to the cold one. The quality of the exchange is characterized by the minimal approach temperature (ΔT_{min}) between the hot and the cold streams. The high level of the heat exchange between streams will be obtained by considering the small value for the ΔT_{min}, and consequently a larger heat transfer area in the exchanger. However, this results in higher investment costs for the heat exchanger. Therefore, the value of ΔT_{min} should be optimized by considering the trade-off between the benefits from the heat recovery and the energy saving, and the investment costs of the heat exchanger.

In the developed model, the ΔT_{min} can be defined as a decision variable in the master optimization. In order to reduce the complexity of the optimization model, a constant value of ΔT_{min}=5 [^oC] is considered for all thermal streams and applied throughout the paper. Therefore, in the present work the temperatures (t_k $\forall k$) refer to the corrected temperatures.

2.2.4. Slave energy integration optimization (EIO)

The next step is the slave optimization. It solves the energy integration optimization (EIO) as a mixed integer linear model (MILP). The principal purpose is to determine the best usage and operating schedule of selected subsystems in order to supply the requirements of the district at a minimum cost. It is solved by robust linear programming methods.

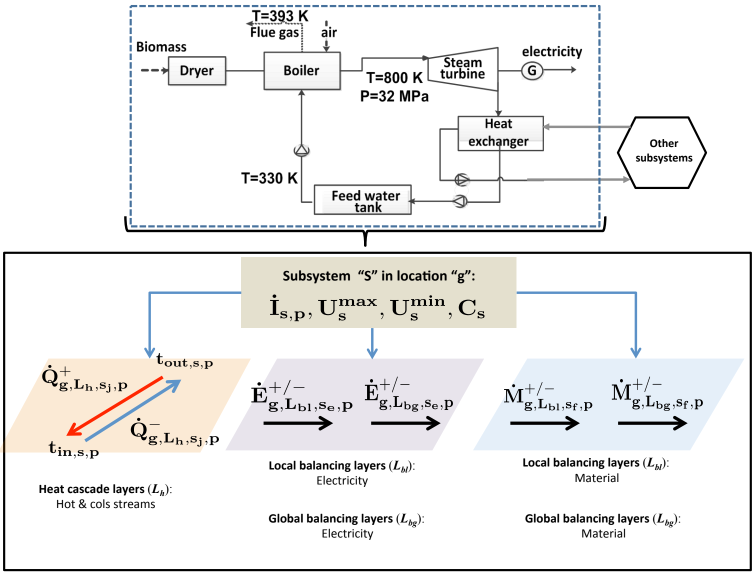

Figure 2: Illustration of a subsystem's streams and layers

The input data (Table 3) used in the slave optimization include the values of the master decision variables and the thermodynamic parameters of subsystems resulting from thermo-economic simulation models (TES).

The objective function of the slave optimization is to minimize the total operating and emissions costs under the energy balance and the heat cascade constraints (Eq.2 to Eq.4). As mentioned before, the system is divided into several subsystems $s \in S$ that are placed in different locations ($g \in G$). For all subsystems ($\forall s = 1, ..., N_S$) the target can be expressed as a function of their usage (on/off condition ($\mathbf{y}_s, \mathbf{y}_{s,p}$)) and their level of utilization ($\mathbf{u}_s, \mathbf{u}_{s,p}$) to be optimized, i.e.:

$$\min_{\mathbf{y}_{s,p},\mathbf{u}_{s,p},\mathbf{y}_s,\mathbf{u}_s,\mathbf{V}_{s'}} \quad \sum_{s=1}^{N_S}\sum_{p=1}^{N_P}(C\dot{O}V1_{s,p} \times \mathbf{y}_{s,p} + C\dot{O}V2_{s,p} \times \mathbf{u}_{s,p}) \times \triangle p \tag{2}$$

$$+\sum_{s=1}^{N_S}(COF1_s \times \mathbf{y}_s + COF2_s \times \mathbf{u}_s) + \sum_{s'=1}^{N_{S'}} \mathbf{COP}_{s'} \tag{3}$$

$$+\sum_{p=1}^{N_P}(\dot{\mathbf{I}}_{\mathbf{p}} \times t_{CO_2} \times \triangle p) + \sum_{s'=1}^{N_{S'}} \mathbf{I}_{s'} \times t_{CO_2} \tag{4}$$

$\mathbf{y}_{s,p}$ is a binary variable for activating the subsystem s at time step p (on/off condition). $\mathbf{u}_{s,p}$ denotes the multiplication factor (the utilization level) for adjusting the reference size of subsystem s at time step p, and $\mathbf{u}_s$ is the maximum utilization level of subsystem s. $C\dot{O}V1_{s,p}$ and $C\dot{O}V2_{s,p}$ represent the linear terms of expenses of subsystem s at time p (i.e. fuel costs, electricity costs, hourly maintenance costs), while $COF1_s$ and $COF2_s$ refer to the linear terms of annual fixed expenses (i.e. fixed maintenance costs). $\dot{\mathbf{I}}_p$ is the environmental impacts of the system at time step p, $\triangle p$ is the duration of time step p, and t_{CO_2} is the emissions tax, which is the decision variable in the master optimization and parameter in the slave optimization. $\mathbf{COP}_{s'}$ and $\dot{\mathbf{I}}_{s'}$ are related to the operating cost and the environmental impacts of the storage tanks s'.

The optimization model has the following constraints, which are grouped into sets of heat cascading and local and global balancing layers (Figure 3):

- Existence of subsystem s at time step p (Eq.5 to Eq.7):

$$U_s^{min} \times \mathbf{y}_{s,p} \leq \mathbf{u}_{s,p} \leq U_s^{max} \times \mathbf{y}_{s,p} \qquad \forall s,p, \quad \mathbf{y}_{s,p} \in \{0,1\} \tag{5}$$

$$\mathbf{y}_{s,p} \leqslant \mathbf{y}_s \qquad \forall s,p \tag{6}$$

$$\mathbf{u}_{s,p} \leqslant \mathbf{u}_s \qquad \forall s,p \tag{7}$$

Eq.5 defines the feasible range of subsystem's multiplication factor ($\mathbf{u}_{s,p}$), where U_s^{min} and U_s^{max} denote the minimum and the maximum utilization level of s. These two parameters are calculated by thermo-economic simulation (TES) models taking into account the subsystems' available capacity ($Y_s \times U_s$). Y_s and U_s are originally the master decision variables.

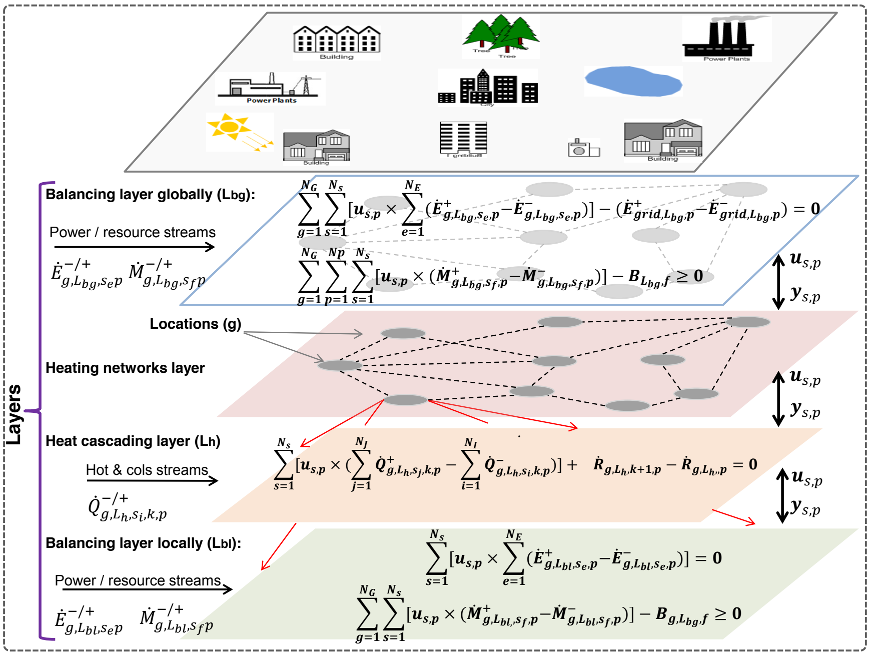

Figure 3: Illustration of a slave energy integration optimization

The maximum multiplication factor ($\mathbf{u}_s$) of subsystem s over all operating periods is defined by Eq.7. It is fixed and equal to 1 for consumers' subsystems ($u_{b,p} = 1$, $u_b = 1$, $\forall b \in S$).

- Heat balance of the corrected temperature interval $k \in K$, in location $g \in G$ and heat cascade layer L_h in location g (Eq.8):

$$[\sum_{s}^{N_S} \mathbf{u}_{s,p} \times (\sum_{j}^{N_{J_s}} \dot{Q}^{+}_{g,L_h,s_j,k,p} - \sum_{i}^{N_{I_s}} \dot{Q}^{-}_{g,L_h,s_i,k,p})] + \dot{\mathbf{R}}_{g,L_h,k+1,p} - \dot{\mathbf{R}}_{g,L_h,k,p} = 0, \tag{8}$$

$$\forall p, k, g, L_h$$

$\dot{Q}^{-}_{g,L_h,s_i,k,p}$ is the reference heat requirement of the cold stream i, of subsystem s, heat cascade layer L_h in location g, temperature interval k, and time step p, while $\dot{Q}^{+}_{g,L_h,s_j,k,p}$ denotes the reference available heat of stream j. These two parameters are originally variables whose values are estimated by thermo-economic simulation models taking into account the reference flow ($\dot{m}_{g,L_h,s_{i/j},k,p}$) of streams $s_{i/j}$ ($\dot{Q}^{-/+}_{g,L_h,s_{i/j},k,p} = \dot{m}_{g,L_h,s_{i/j},k,p} \times C_p \times (t_{k+1} - t_k)$).

$\dot{\mathbf{R}}_{g,L_h,k,p}$ is a continuous variable for the residual heat from the temperature interval k and heat cascade layer L_h in location g at time step p. There is a possibility of cascading the residual heat from the higher temperature interval $(k+1)$ to the lower one (k) in each location and in each heat cascade layer. The heat exchange between two different layers of heat cascading (L_h) is forbidden (Eq.8). It is defined in order to take into account the heat exchange restrictions. The heat transfer between locations is only allowed through the heating distribution networks (Sec 3).

- Overall heat balance of each heat cascade layer L_h in location g: The set of temperature intervals, k, is defined taking into account the corrected temperature levels ($t \in T$) of streams in each location and in each heat cascade layer. The minimum and the maximum corrected temperatures of each interval are t_k and $t_{k+1} \in T$. The maximum corrected temperature level is equal to $T_{max} = t_{N_K+1}$, and the minimum one is $T_{min} = t_1$. In order to close the balance in the heat cascade layer L_h, the residual heat from the last temperature interval $(N_K + 1)$ and to the first one is equal to zero (Eq.9).

$$\dot{\mathbf{R}}_{g,L_h,k,p} \geq 0, \quad \dot{\mathbf{R}}_{g,L_h,1,p} = 0, \quad \dot{\mathbf{R}}_{g,L_h,N_K+1,p} = 0, \quad \forall p, g, L_h, k \quad (9)$$

- Electricity balance in each location (local balancing) or between locations (global balancing); Eq.10 refers to the local balancing of the electricity production and consumption in each location;

$$\sum_{s}^{N_S} \mathbf{u}_{s,p} \times [\sum_{e}^{N_{E_s}} (\dot{E}^{+}_{g,L_{bl},s_e,p} - \dot{E}^{-}_{g,L_{bl},s_e,p})] = 0, \qquad \forall g, L_{bl}, p \qquad (10)$$

$\dot{E}^{-}_{g,L_{bl},s_e,p}$ and $\dot{E}^{+}_{g,L_{bl},s_e,p}$ are the reference electricity consumption and production of subsystem s, in local balancing layer L_{bl} in location g, at time step p. These two parameters are originally variables whose values are estimated by thermo-economic simulation models.

Eq.11 and Eq.12 present the balancing constraints between locations (globally) through the grid.

$$\sum_{g}^{N_G}[\sum_{s}^{N_S}\mathbf{u}_{s,p}\times\sum_{e}^{N_{E_s}}(\dot{E}^{+}_{g,L_{bg},s_e,p}-\dot{E}^{-}_{g,L_{bg},s_e,p})]-(\dot{\mathbf{E}}^{+}_{grid,L_{bg},p}-\dot{\mathbf{E}}^{-}_{grid,L_{bg},p})=0,\forall L_{bg},p \tag{11}$$

$$\dot{\mathbf{E}}^{+}_{grid,L_{bg},p}\geqslant 0,\quad \dot{\mathbf{E}}^{-}_{grid,L_{bg},p}\geqslant 0,\quad \forall L_{bg},p \tag{12}$$

$\dot{\mathbf{E}}^{+}_{grid,L_{bg},p}$ and $\dot{\mathbf{E}}^{-}_{grid,L_{bg},p}$ are continuous variables referring to the electricity export and import from the main grid in layer L_{bg} at time step p. There is a possibility of defining several L_{bl} and L_{bg} layers to differentiate the electricity from different sources or different type of grids.

- Resource/product balance in each location (locally): The resource/product balance is defined locally in each location by Eq.13.

$$\sum_{s}^{N_S}\sum_{p}^{N_P}\Big[\mathbf{u}_{s,p}\times(\dot{M}^{+}_{g,L_{bl},s_f,p}-\dot{M}^{-}_{g,L_{bl},s_f,p})\Big]\times\triangle p+B_{g,L_{bl},f}\geqslant 0,\forall g,L_{bl},f \tag{13}$$

$\dot{M}^{-}_{g,L_{bl},s_f,p}$ and $\dot{M}^{+}_{g,L_{bl},s_f,p}$ denote the reference consumption and production level of material f (i.e. water, products, waste, fuels) in subsystem s, and local layer L_{bl} in location g. $B_{g,L_{bl},f}$ refers to the maximum availability of material f, in local layer L_{bl} in location g. If $B_{g,L_{bl},f}$ is restricted for each time step, then Eq.13 will be expressed by Eq.14;

$$\sum_{s}^{N_S}\Big[\mathbf{u}_{s,p}\times(\dot{M}^{+}_{g,L_{bl},s_f,p}-\dot{M}^{-}_{g,L_{bl},s_f,p})\Big]\times\triangle p+B_{g,L_{bl},f,p}\geqslant 0,\forall g,L_{bl},f,p \tag{14}$$

As an example, $B_{g,L_{bl},f}$ and $B_{g,L_{bl},f,p}$ can refer to the local storage or indigenous resources. These two parameters are originally decision variables in the master optimization.

A positive variable $\dot{\mathbf{F}}_{g,L_{bl},f,p}$ in Eq.15 is equal to the local material consumptions of type f, and layer L_{bl} in location g, at time step p;

$$\dot{\mathbf{F}}_{g,L_{bl},f,p}=\sum_{s}^{N_S}\mathbf{u}_{s,p}\times(\dot{M}^{-}_{g,L_{bl},s_f,p}-\dot{M}^{+}_{g,L_{bl},s_f,p}),\forall g,L_{bl},f,p \tag{15}$$

$$\dot{\mathbf{F}}_{g,L_{bl},f,p} \geqslant 0, \qquad \forall g, L_{bl}, f, p \tag{16}$$

- Resource/product balance across locations (globally): The resource/product can be balanced between locations through the transportation pathway (Eq.17 and Eq.18).

$$\sum_{g}^{N_G}\sum_{s}^{N_S}\sum_{p}^{N_P}\Big[\mathbf{u}_{s,p} \times (\dot{M}^{+}_{g,L_{bg},s_f,p} - \dot{M}^{-}_{g,L_{bg},s_f,p})\Big] \times \triangle p + B_{L_{bg},f} \geqslant 0, \forall L_{bg}, f \tag{17}$$

$$\sum_{g}^{N_G}\sum_{s}^{N_S}\Big[\mathbf{u}_{s,p} \times (\dot{M}^{+}_{g,L_{bg},s_f,p} - \dot{M}^{-}_{g,L_{bg},s_f,p})\Big] \times \triangle p + B_{L_{bg},f,p} \geqslant 0, \forall L_{bg}, f, p \tag{18}$$

$\dot{\mathbf{F}}_{L_{bg},f,p}$ in Eq.19 denotes the net material (i.e. water, products, waste, fuels) import of type f from abroad or from storage systems, in global layer L_{bg} at time step p. It can be positive or negative (import/export):

$$\dot{\mathbf{F}}_{L_{bg},f,p} = \sum_{g}^{N_G}\sum_{s}^{N_S}\mathbf{u}_{s,p} \times (\dot{M}^{-}_{g,L_{bg},s_f,p} - \dot{M}^{+}_{g,L_{bg},s_f,p}), \qquad \forall L_{bg}, f, p \tag{19}$$

- The total environmental impacts of subsystems and the net electricity and materials import are considered as the overall system emissions (Eq.20 to Eq.22):

$$\dot{\mathbf{I}}_p = (\sum_{s}^{N_S}\mathbf{u}_{s,p} \times \dot{I}_{s,p}) + \sum_{f}^{N_F}\dot{\mathbf{I}}_{f,p} + \dot{\mathbf{I}}_{grid,p} \quad \forall p \tag{20}$$

$$\dot{\mathbf{I}}_{grid,p} = \sum_{L_{bg}}^{N_{L_{bg}}}(\dot{\mathbf{E}}^{+}_{grid,L_{bg},p} - \dot{\mathbf{E}}^{-}_{grid,L_{bg},p}) \times m^{grid}_{I,L_{bg}} \quad \forall p \tag{21}$$

$$\dot{\mathbf{I}}_{f,p} = (\sum_{L_{bg}}^{N_{L_{bg}}}\dot{\mathbf{F}}_{L_{bg},f,p} + \sum_{g}^{N_G}\sum_{L_{bl}}^{N_{L_{bl}}}\dot{\mathbf{F}}_{g,L_{bl},f,p}) \times m_{f,I} \quad \forall p \tag{22}$$

$\dot{I}_{s,p}$ refers to the reference environmental impacts of subsystem s at time p. $\dot{\mathbf{I}}_{f,p}$ is the total impacts of material f, which is imported/exported from/to abroad or local/global storage systems or indigenous resources, at time step p, over global (L_{bg}) and local (L_{bl}) layers and locations. $\dot{\mathbf{I}}_{grid,p}$ measures the environmental impacts of the electricity from the grid, over L_{bg} layers, at time p. The total impacts of the system at time p is denoted by $\dot{\mathbf{I}}_p$. The environmental impacts of the electricity import from the grid and materials are denoted by $m^{grid}_{I,L_{bg}}$ and $m_{f,I}$ respectively. The environmental impacts of the electricity from the grid ($m^{grid}_{I,L_{bg}}$) can be defined for each L_{bg} layer.

- Daily thermal storage is used to manage the energy demand fluctuation during a cyclic period [21]. It allows for better utilization of equipment and avoiding over estimation of backup equipment' capacity. However, there should be a trade off between the costs and environmental impacts of conversion technologies and the storage facilities.

  In the present work a thermal storage subsystem ($s' \in S' \subseteq S$) is discretized into a finite number of temperature levels, $t_{k'} \in T' \subseteq T$, between its maximum and minimum feasible limits, $T'_{min} \geqslant T_{min}$ and $T'_{max} \leqslant T_{max}$. The temperature interval of the storage is denoted by $k' \in K' \subseteq K$ with a temperature level of $t_{k'}$ to $t_{k'+1}$. The maximum feasible volume, $V^{max}_{s'}$, and the number of temperature discretization of each heat storage facility are the master decision variables.

  The heat content of the cyclic storage must be equal at the beginning and at the end of a period (Eq 23).

$$\sum_{p}^{N_P}\sum_{k'=1}^{N_{K'}}\left(\sum_{j}^{N_{J_s}}\mathbf{u}'_{s'_j,k',p}\times\dot{Q}^{+}_{s'_j,k',p}-\sum_{i}^{N_{I_s}}\mathbf{u}'_{s'_i,k',p}\times\dot{Q}^{-}_{s'_i,k',p}\right)\times\triangle p=0\quad\forall s'\in S' \tag{23}$$

  $\dot{Q}^{-}_{s'_i,k',p}$ is a reference heat discharging of the storage s' in the interval k' at time p, while $\dot{Q}^{+}_{s'_j,k',p}$ refers to the reference heat charging. The utilization of charging and discharging modes of the storage in each time step and temperature interval are $\sum_j^{N_{J_s}}\mathbf{u}'_{s'_j,k',p}$ and $\sum_i^{N_{I_s}}\mathbf{u}'_{s'_i,k',p}$ respectively, with the total charging load of $\sum_j^{N_{J_s}}\mathbf{u}'_{s'_j,k',p}\times\dot{Q}^{+}_{s'_j,k',p}$.

  The storage fluid content ($\mathbf{V}_{s',t_{k'},p}\geqslant 0$) in each temperature level of the storage tank at the end of time step p is calculated by taking into account the initial volume ($\mathbf{V}^0_{s',t_{k'}}$), the charging rate to the upper temperature level, the discharging rate to the lower temperature level, the heat losses, the specific heat capacity and the density of the storage fluid. It is refer to [21] for the detailed explanation of the thermal storage.

The operating costs ($\mathbf{COP}_{s'}$), the investment costs ($\mathbf{CI}_{s'}$) and the environmental impacts ($\mathbf{I}_{s'}$) of the storage tank as a function of its volume are considered in the master and the slave objective functions.

- Heating/Cooling distribution networks: There is a possibility of transferring heat from one location to others. It is done through the heating distribution networks. The detail model of the distribution networks is presented in Sec 3.

2.2.5. Environomic evaluation (EE)

The selected superstructure in the master level and the results of the slave optimization are used in the environomic evaluation (EE) phase to calculate objective functions of the master optimization, which are system's efficiency (EFF), total annual costs (TAC) and M_{CO_2} emissions as an environmental impacts.

Energetic objective: system's efficiency (EFF)

The system efficiency is calculated by correlation 24. It takes into account the energy of the services and the resources, and considers thermal and mechanical energy as being equivalent. The electricity import is substituted by an equivalent amount of natural gas required for generating the same amount of the electricity in a combined cycle with an energy efficiency of η_γ=58% [26].

$$\mathbf{EFF} = \frac{\sum_p (\dot{\mathbf{EB}}_p + \sum_{L_{bg}} \dot{\mathbf{E}}^-_{grid,L_{bg},p}) \times \triangle p}{\sum_p (\dot{\mathbf{F}}_p + \sum_{L_{bg}} \dot{\mathbf{E}}^+_{grid,L_{bg},p}/\eta_\gamma) \times \triangle p} \tag{24}$$

With:

$$\dot{\mathbf{F}}_p = \sum_f (\sum_{L_{bg}} \dot{\mathbf{F}}_{L_{bg},f,p} + \sum_{g,L_{bl}} \dot{\mathbf{F}}_{g,L_{bl},f,p}) \quad \forall p \tag{25}$$

$$\dot{\mathbf{EB}}_p = \sum_{g,b} \mathbf{u}_{b,p} \times (\sum_{L_h,i,k} \dot{Q}^-_{g,L_h,b_i,k,p} + \sum_{L_{bl},e} \dot{E}^+_{g,L_{bl},b_e,p} + \sum_{L_{bg},e} \dot{E}^+_{g,L_{bg},b_e,p}) \quad \forall p \tag{26}$$

In Eq.25 and Eq.26, $b \in S$ denotes the building subsystem with $\mathbf{u}_{b,p} = 1$ and the total energy demand of $\dot{\mathbf{EB}}_p$. While $\dot{\mathbf{F}}_p$ refers to the overall material (i.e. products, waste, fuels) consumption in the global system. Based on the definition of the system boundaries, the local/indigenous materials ($\dot{\mathbf{F}}_{g,L_{bl},f,p}$) can be excluded from Eq.25.

Economic objective: total annual costs (TAC)

The economic performance is defined by the capital investment and by the operating (i.e. fuel and the electricity costs) and maintenance expenses. If market prices for commercial equipment or manufacturer's data are not available, then the capital costs are estimated based on the size and the type of construction material of each equipment and by applying the correlations given in [27].

$$\mathbf{TAC} = \sum_{s=1}^{N_S}\sum_{p=1}^{N_P}(C\dot{O}V1_{s,p} \times \mathbf{y}_{s,p} + C\dot{O}V2_{s,p} \times \mathbf{u}_{s,p}) \times \triangle p \tag{27}$$

$$+\sum_{s=1}^{N_S}(COF1_s \times \mathbf{y}_s + COF2_s \times \mathbf{u}_s) + \sum_{s'=1}^{N_{S'}} \mathbf{COP}_{s'} \tag{28}$$

$$+\sum_{s=1}^{N_S}\mathbf{CI}_s \times \frac{i.(1+i)^{n_s}}{(1+i)^{n_s-1}} + \sum_{s'=1}^{N'_S}\mathbf{CI}_{s'} \times \frac{i.(1+i)^{n_s}}{(1+i)^{n_s-1}} \tag{29}$$

The total annual operating and maintenance costs are calculated by Eq.27 and Eq.28, which are the results of the slave optimization. The linear terms of the operating costs, $C\dot{O}V1_{s,p}$ and $C\dot{O}V2_{s,p}$, include the expenses/benefits of the fuel and the electricity consumptions/productions. Eq.29 calculates the annual investment costs taking into account the equipment lifetime (n_s) and the interest rate (i). $\mathbf{CI}_s$ (Eq.30) is the total investment costs of equipment s estimated by applying the correlations given in [27].

$$\mathbf{CI}_s = (1+\alpha_1) \times \mathbf{C}_{BM,s} \qquad \forall s \tag{30}$$

$$\mathbf{C}_{BM,s} = (B_{1,s} + B_{2,s} \times F_{M,s} \times F_{P,s}) \times \frac{I_s}{I_{ref,s}} \times \mathbf{C}_{pc,s} \qquad \forall s \tag{31}$$

$$log(\mathbf{C}_{pc,s}) = K_{1,s} + K_{2,s}log(\mathbf{U}_s \times \mathbf{Y}_s) + K_{3,s}(log(\mathbf{U}_s \times \mathbf{Y}_s))^2 \quad \forall s, \tag{32}$$

The Bare-Module cost ($C_{BM,s}$) is defined as a function of equipment's purchase cost ($C_{pc,s}$). It is adjusted by Marshall and Swift cost index for the reference year ($I_{ref,s}$) and the actual year (I_s), material (F_M) and pressure factors (F_M) that take into account the effect of material and operating pressure changes of equipment compare to the base case conditions. B_1 and B_2 are constants computed based on the existing equipment cost databases, while K_1, K_2 and K_3 are empirical constants derived from the cost database for each equipment. α_1 represents additional cost related to the construction of the plant. According to [27] the conventional value for this factor is 0.18. The installed capacity of subsystem s is $U_s \times Y_s$, which are decision variables in the master optimization.

Environmental impacts in terms of CO_2 emissions

In the present context of finding ways to decrease CO_2 emissions the overall life cycle environmental impacts from the resource extraction along the production chain to the final products have to be considered for designing the district energy systems. This can be done by integrating Life Cycle Assessment (LCA). LCA is a well-established method that allows to assess the environmental performance of a resource, a process or a service taking into account its full life cycle.

The life cycle assessment can be included in the thermo-economic optimization of energy systems [28]. For this purpose, the LCI is defined for reference size of each subsystem taking into account resources and products. Based on this definition the environmental performance can be included as an objective in the multi-objectives environomic optimization (Eq.

$$\mathbf{M_{CO_2}} = \sum_{p=1}^{N_P}[\sum_{s=1}^{N_S}(\mathbf{u}_{s,p} \times \dot{I}_{s,p}) + \sum_{f=1}^{N_F}\dot{\mathbf{I}}_{\mathbf{f},\mathbf{p}} + \dot{\mathbf{I}}_{\mathbf{E_p}}] + \sum_{s'=1}^{N_{S'}}\mathbf{I}_{s'} \tag{33}$$

2.2.6. Post-processing phase

After all iterations of the master optimization the results will be presented by the Pareto optimal frontier. The aim of the post-processing phase is to analyze results once the optimization phase has been completed and reached the Pareto optimal frontier. Since each solution included in the Pareto frontier is optimal with regard to the chosen objectives, it is not obvious which specific solution has to be selected.

Multi-criteria evaluation can be applied to choose the solution that will finally be implemented. The success of this phase strongly relies on the collaboration between the decision-makers, stake-holders and engineers.

3. Network design and operation optimization model

The network design model is used to optimize the district networks' layout and temperatures, together with configurations and locations of centralized and decentralized plants. The investment costs, the pipelines' length and the heat losses of networks are determined by using the geographical information system (GIS data).

As explained in Sec 2.2.4, the model comprises several subsystems ($s \in S$) which are placed in different locations ($g \in G$) with geographical coordinates g_x and g_y. The heat transfer between locations is only allowed through the network's pipelines ($N_{g,g'}$, g & $g' \in G$). The geographical information (GIS) data is used to define the possible routes and the real distance between two locations. The corrected temperatures level of streams, which are exchanging with the heating (h) and cooling (c) networks, should be between the network's corrected design supply ($T_{out}^{h/c}$) and return ($T_{in}^{h/c}$) temperatures. $T_{out}^{h/c}$ and $T_{in}^{h/c}$ are originally decision variables whose values are fixed by the master optimization. The set of temperature intervals ($k \in K$) of the system is defined taking into account the corrected temperature levels ($t \in T$) of all heat cascading streams. The minimum and the maximum corrected temperatures of each interval are presented by t_k and $t_{k+1} \in T$. A sub set of K between $T_{out}^{h/c}$ and $T_{in}^{h/c}$ is considered as the network's feasible temperature intervals ($k'' \in K'' \subseteq K$), with the corrected temperature level of $t_{k''}$ to $t_{k''+1}$ ($t_{k''} \in T'' \subseteq T$ and $T_{in}^{h/c} \leqslant t_{k''} \leqslant T_{out}^{h/c}$).

The proposed slave optimization model (Sec 2.2.4) is modified and developed by adding the following network's constraints;

- Heat balance of the temperature interval $k'' \in K''$, in location $g \in G$ and heat cascade layer L_h (Eq.34 to Eq.35):

$$[\sum_{s}^{N_S} \mathbf{u}_{s,p} \times (\sum_{j}^{N_{J_s}} \dot{Q}^{+}_{g,L_h,s_j,k'',p} - \sum_{i}^{N_{I_s}} \dot{Q}^{-}_{g,L_h,s_i,k'',p})] + (\dot{\mathbf{R}}_{g,L_h,k''+1,p} - \dot{\mathbf{R}}_{g,L_h,k'',p}) + (\dot{\mathbf{Q}}^{+}_{N_g,L_h,k'',p} - \dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p}) = 0, \quad \forall p, k'', g, L_h \tag{34}$$

$$\dot{\mathbf{Q}}^{+}_{N_g,L_h,k'',p} \geq 0, \quad \dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p} \geq 0, \quad \forall p, g, L_h, k'' \tag{35}$$

$\dot{Q}^{-}_{g,L_h,s_i,k'',p}$ is the reference heat requirement of the cold stream i, of subsystem s, heat cascade layer L_h in location g, temperature interval

k'', at time step p, while $\dot{Q}^{+}_{g,L_h,s_j,k'',p}$ denotes the reference available heat of stream j. These two parameters are originally variables whose values are estimated by thermo-economic simulation models (TES, Sec.2.2.2) taking into account the reference flow ($\dot{m}_{g,L_h,s_{i/j},k'',p}$) of streams $s_{i/j}$ ($\dot{Q}^{-/+}_{g,L_h,s_{i/j},k'',p} = \dot{m}_{g,L_h,s_{i/j},k'',p} \times C_p \times (t_{k''+1} - t_{k''})$). $\dot{\mathbf{Q}}^{+}_{N_g,L_h,k'',p}$ is the available ($^{+}$) heat comes from other locations and $\dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p}$ measures the residual ($^{-}$) heat from temperature interval k'' which transfers to other locations through the distribution networks.

- Heat balance through the network's pipeline in location $g \in G$, heat cascade layer L_h and temperature interval k'' during time step p (Eq.36 and Eq.37):

$$\sum_{g}^{N_G} (\mathbf{u}_{N_{g,g'},L_h,p} \times \dot{Q}^{+}_{N_{g,g'},L_h,k'',p} - \dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p}) - \dot{\mathbf{Q}}^{+}_{N_{g'},L_h,k'',p} = 0 \quad (36)$$

$$\forall L_h, k'', p, g', g \neq g'$$

$$\sum_{g'}^{N_G} (\mathbf{u}_{N_{g,g'},L_h,p} \times \dot{Q}^{-}_{N_{g,g'},L_h,k'',p}) - \dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p} = 0 \quad (37)$$

$$\forall L_h, k'', p, g, g \neq g'$$

$\dot{Q}^{+}_{N_{g,g'},L_h,k'',p}$ denotes the reference heat transfer from location g to g' in heat cascade layer L_h. $\mathbf{u}_{N_{g,g'},L_h,p}$ refers to the utilization level of each pipeline ($N_{g,g'}$). It is a continuous decision variable in the slave optimization.

- Heat loss through the network's pipeline ($\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p}$) is obtained considering a heat loss factor ($f^{loss}_{L_h,k''}$) for a given reference heat transfer load ($\dot{Q}^{+}_{N_{g,g'},L_h,k'',p}$) in heat cascade layer L_h (Eq.38). The heat loss factor ($f^{loss}_{L_h,k''}$) is considered proportional to the supply and the ground (T_{gnd}) temperature differences (Eq.39);

$$\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p} \geqslant \mathbf{u}_{N_{g,g'},L_h,p} \times f^{loss}_{L_h,k''} \times \dot{Q}^{+}_{N_{g,g'},L_h,k'',p} \qquad \forall g', g, L_h, g \neq g' \quad (38)$$

$$f^{loss}_{L_h,k''} = f^{loss}_{0,L_h} \times \frac{t_{k''+1} - T_{gnd}}{T^{h/c}_{out} - T_{gnd}} \qquad \forall L_h, k'' \tag{39}$$

The reference heat loss factor, f^{loss}_{0,L_h}, is estimated based on the insulation thickness and material of the chosen pipe. There is a smaller heat loss factor for a pipe with the higher insulation level. Meanwhile, the investment costs will be higher. The thermo-economic analysis of the pipe insulation in district energy systems has been investigated by [29]. In the present work, in order to take into account the quality of the pipeline in the optimization, there are two possibilities; define f^{loss}_{0,L_h} as a decision variable in the master optimization and chose the best one on the Pareto, or define several network heat cascading layer (L_h) in the slave optimization with the corresponding f^{loss}_{0,L_h} and the operating and the investment costs and chose the best one. The second option will increase the size of the slave MILP optimization model.

During the operating periods when the heat demand is lower than the minimum design flow rate of the pipeline (Summer period), the networks should still operate at the partial load with the minimum design flow rate. During these periods the heat losses are estimated by Eq.40 with the constant heat loss of $Q^{loss,0}_{N_{g,g'},L_h,k''}$.

$$\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p} \geqslant \mathbf{y}_{N_{g,g'},L_h} \times \dot{Q}^{loss,0}_{N_{g,g'},L_h,k''} \qquad \forall g', g, L_h, g \neq g' \tag{40}$$

- The maximum utilization level of each pipeline ($\mathbf{u}_{N_{g,g'},L_h}, g \neq g'$) is defined as (Eq.41):

$$\mathbf{u}_{N_{g,g'},L_h,p} \leq \mathbf{u}_{N_{g,g'},L_h} \qquad \forall g', g, L_h, p, g \neq g' \tag{41}$$

- The existence of pipeline $N_{g,g'}$, $g \neq g'$ is defined by a variable $\mathbf{y}_{N_{g,g'},L_h}$ (Eq.42 and Eq.43):

$$U^{min}_{N_{g,g'},L_h} \times \mathbf{y}_{N_{g,g'},L_h,p} \leqslant \mathbf{u}_{N_{g,g'},L_h,p} \leq U^{max}_{N_{g,g'},L_h} \times \mathbf{y}_{N_{g,g'},L_h,p} \tag{42}$$

$$\mathbf{y}_{N_{g,g'},L_h,p} \in \{0,1\}, \quad \forall p, L_h, g', g, g \neq g'$$

$$\mathbf{y}_{N_{g,g'},L_h,p} \leqslant \mathbf{y}_{N_{g,g'},L_h}, \quad \forall p, L_h, g', g, g \neq g' \tag{43}$$

$\mathbf{y}_{N_{g,g'},L_h,p}$ is a binary variable for activating the pipeline $N_{g,g'}$ at time p. Eq.42 also defines the feasible range of the utilization level for each pipeline ($\mathbf{u}_{N_{g,g'},L_h}$), where $U^{min}_{N_{g,g'},L_h}$ and $U^{max}_{N_{g,g'},L_h}$ denote the minimum and the maximum feasible utilization level of pipeline $N_{g,g'}$ in layer L_h. These two parameters are calculated by thermo-economic simulation (TES, Sec. 2.2.2) models taking into account the minimum and maximum allowable flow speed in the pipeline. If the pipeline is already exist then $\mathbf{y}_{N_{g,g'},L_h} = 1$.

- The diameter of each pipe ($\mathbf{d}_{N_{g,g'}}$) is optimized by considering the investment cost and the maximum heat load ($\dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h}$) transferred through the networks (Eq.44 and Eq.45). Cross section area of the pipeline ($\mathbf{A}_{N_{g,g'},L_h}$) is considered in order to express Eq.45 in a linear form.

$$\mathbf{u}_{N_{g,g'},L_h,p} \times \dot{Q}^{+}_{N_{g,g'},L_h,k'',p} \leq \dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h} \qquad \forall g', g, L_h, p, k'' \tag{44}$$

$$\left(\frac{\pi}{4} \times \mathbf{d}^2_{N_{g,g'},L_h}\right) = \frac{\dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h}}{\left[\rho \times \nu \times C_p \times (T^{h/c}_{out} - T^{h/c}_{in})\right]} \qquad \forall g', g, L_h, \tag{45}$$

$$(\mathbf{A}_{N_{g,g'},L_h}) = \frac{\dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h}}{\left[\rho \times \nu \times C_p \times (T^{h/c}_{out} - T^{h/c}_{in})\right]} \qquad \forall g', g, L_h, \tag{46}$$

ν [m/s] is a design flow velocity of the fluid (i.e. 3 m/s [30]).

- Pumping power through the network's pipeline in global balancing layer $L'_{bg} \subseteq L_{bg}$ during time step p (Eq.47)

$$\dot{\mathbf{E}}^{-}_{N,L'_{bg},p} \geqslant \sum_{g}^{N_G} \sum_{g'}^{N_G} \sum_{L_h}^{N_{L_h}} (\dot{E}1^{-}_{N_{g,g'},L'_{bg}} \times \mathbf{y}_{N_{g,g'},L_h,p} + \dot{E}2^{-}_{N_{g,g'},L'_{bg}} \times \mathbf{u}_{N_{g,g'},L_h,p}) \qquad \forall L'_{bg}, p, g \neq g' \tag{47}$$

$\dot{E}1^{-}_{N_{g,g'},L'_{bg}}$ and $\dot{E}2^{-}_{N_{g,g'},L'_{bg}}$ (Eq.47) denotes the linear terms of the reference pumping power from location g to g' in global balancing layer L'_{bg}. These two parameters are estimated by thermo-economic simulation model (TES, Sec.2.2.2) taking into account the piecewise linearization technique [25], the $U^{max/min}_{N_{g,g'},L_h}$, the reference heat transfer ($\dot{Q}^{+}_{N_{g,g'},L_h,k'',p}$) through the pipeline from location g to g' and corresponding distance ($dl_{N_{g,g'}}$). It is refer to [30] for more information, and [31] for an application.

The total pumping power ($\dot{\mathbf{E}}^{-}_{N,L'_{bg},p}$) is included in the electricity global balancing layer (Eq.48 and Eq.49). The pumping power will be decreased by increasing the diameter of the pipe ($\mathbf{d}_{N_{g,g'}}$ in Eq.45). However, this results in higher investment costs (Table 4). Therefore, in order to optimize the diameter of the pipe and to make the slave optimization linear, the design flow velocity (ν [m/s]) is defined as a decision variable in the master optimization.

$$\sum_{g}^{N_G}[\sum_{s}^{N_S}\mathbf{u}_{s,p}\times\sum_{e}^{N_{E_s}}(\dot{E}^{+}_{g,L'_{bg},s_e,p}-\dot{E}^{-}_{g,L'_{bg},s_e,p})]-\dot{\mathbf{E}}^{-}_{N,L'_{bg},p}$$
$$-(\dot{\mathbf{E}}^{+}_{grid,L'_{bg},p}-\dot{\mathbf{E}}^{-}_{grid,L'_{bg},p})=0,\forall L'_{bg},p \tag{48}$$

$$\dot{\mathbf{E}}^{+}_{grid,L'_{bg},p}\geqslant 0,\quad \dot{\mathbf{E}}^{-}_{grid,L'_{bg},p}\geqslant 0,\quad \forall L'_{bg},p \tag{49}$$

As mentioned before, during the operating periods when the heat demand is lower than the minimum design flow rate, the networks should still operate with the minimum design flow rate. During these periods the pumping power is estimated by Eq.50 with the constant pumping power of $\dot{E}^{0}_{N_{g,g'},L'_{bg}}$ (see supplementary Figure S1).

$$\dot{\mathbf{E}}^{-}_{N,L'_{bg},p}\geqslant\sum_{g}^{N_G}\sum_{g'}^{N_G}\sum_{L_h}^{N_{L_h}}\dot{E}^{0}_{N_{g,g'},L'_{bg}}\times\mathbf{y}_{N_{g,g'},L_h}\quad\forall L'_{bg},p,g\neq g' \tag{50}$$

The variable operating cost of the distribution networks corresponding to the pumping costs and heat losses are computed by Eq.51 and will be added to Eq.2 and Eq.27. The heat loss, $\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p}$, is a cold stream in the heat cascade balancing layer L_h (Eq.34 and Eq.36), which is heated up by the available hot streams from conversion technologies. Therefore, the heat losses costs are already accounted in the operating costs of conversation technologies (Eq.2 and Eq.27).

$$\mathbf{COVN} = \sum_{p}^{N_p}\sum_{g}^{N_G}\sum_{g'}^{N_G} \dot{EP}_{L'_{bg},p} \times \dot{\mathbf{E}}^{-}_{N,L'_{bg},p} \times \triangle p, \tag{51}$$

$\dot{EP}_{L'_{bg},p}$ [€/kWh] refers to the electricity cost in layer L'_{bg}. Rest of the electricity consumption and production of the system are accounted in the operating costs of each subsystem (TES, Sec. 2.2.2).

The maintenance and fixed operating costs of the distribution network, as a function of its length ($dl_{N_{g,g'}}$) and its cross section area ($\mathbf{A}_{N_{g,g'},L_h}$), are computed by Eq.52. It will be added to the objective function of the slave optimization (Eq.3) and **TAC** (Eq.28);

$$\begin{aligned}\mathbf{COFN}_{L_h} = \sum_{g}^{N_G}\sum_{g'}^{N_G}[dl_{N_{g,g'}} \times (COFN1_{L_h} \times \mathbf{y}_{N_{g,g'},L_h} \\ +COFN2_{L_h} \times \mathbf{A}_{N_{g,g'},L_h}], \quad \forall L_h, g \neq g'\end{aligned} \tag{52}$$

$COFN1_{L_h}$ [€/m] and $COFN2_{L_h}$ [€/m^3] refer to the linear terms of network's maintenance and fixed operating costs (TES, Sec. 2.2.2).

Table 4 refers to the typical investment costs of the network [32]. Piecewise linearization techniques [25] are used to define the discrete network investment costs as a set of linear segments. As a result, the investment costs, as a function of its length ($dl_{N_{g,g'}}$) and its cross section area ($\mathbf{A}_{N_{g,g'},L_h}$), are computed by Eq.53 [32] and will be added to the **TAC** (Eq.29);

$$\begin{aligned}\mathbf{CIN}_{L_h} = \sum_{g}^{N_G}\sum_{g'}^{N_G}[dl_{N_{g,g'}} \times (CIN1_{L_h} \times \mathbf{y}_{N_{g,g'},L_h} \\ +CIN2_{L_h} \times \mathbf{A}_{N_{g,g'},L_h})], \quad \forall L_h, g \neq g'\end{aligned} \tag{53}$$

$CIN1_{L_h}$ [€/m] and $CIN2_{L_h}$ [€/m^3] denote the linear terms of network investment costs. In the present work, $CIN1_{L_h}$=929 [€/m] and $CIN2_{L_h}$=23306 [€/m^3] have been calibrated on dada from Table 4.

The environmental impacts of distribution network is measured by Eq.54 and will be added to Eq.4 and Eq.33;

$$\mathbf{IN}_{L_h} = \sum_{g}^{N_G} \sum_{g'}^{N_G} (IN_{L_h} \times dl_{N_{g,g'}} \times \mathbf{A}_{N_{g,g'},L_h}) \quad \forall L_h, g \neq g' \tag{54}$$

IN_{L_h} refers to the reference environmental impacts of the pipeline in layer L_h.

Note that the temperature drops are not explicitly considered in the proposed model.

4. Transportation and logistics optimisation

The transportation is a well known problem in which resources/ materials/ products are to be shipped from several origins to several destinations at minimum overall cost.

In the district energy system, the transportation of resources/ materials/ products from warehouses or production locations to consumption sides should be optimized. Resources and products are received from plants or warehouses, which are defined in the **global balancing layers** (L_{bg}), to transship to destinations through exist roads and transportation systems. For each connection between locations there is a shipping cost. The optimization problem is to find the lowest-cost plan of shipments that uses only the available roads and transportation system, respects the capacities, and meets the requirements of the destination. Moreover, the location of a new warehouse or a storage system also can be optimized.

The shipping network is modeled by considering a set of locations ($g \in G$) and a set of connections between locations ($X_{g,g'}$). There is a possibility of producing ($^+$) products/resources/materials locally ($\mathbf{u}_{s,p} \times \dot{M}^+_{g,L_{bg},s_f,p}$) in subsystem $s \in S$, or importing ($^+$) from other locations ($\dot{\mathbf{M}}^+_{g,L_{bg},f,p}$) inside the system boundaries, or importing from outside the system boundaries ($\dot{\mathbf{F}}^+_{g,L_{bg},f,p}$). The available resources/materials/products in layer L_{bg} may consume by other subsystems in the same location ($\mathbf{u}_{s,p} \times \dot{M}^-_{g,L_{bg},s_f,p}$) or may transport to other locations ($\dot{\mathbf{M}}^-_{g,L_{bg},f,p}$) or may export ($^-$) abroad ($\dot{\mathbf{F}}^-_{g,L_{bg},f,p}$)

as it is expressed by Eq.55;

$$[\sum_{s}^{N_S} \mathbf{u}_{s,p} \times (\dot{M}^{-}_{g,L_{bg},s_f,p} - \dot{M}^{+}_{g,L_{bg},s_f,p})] - (\dot{\mathbf{M}}^{+}_{g,L_{bg},f,p} - \dot{\mathbf{M}}^{-}_{g,L_{bg},f,p}) = 0, \forall L_{bg}, f, p, g \quad (55)$$

$$\dot{\mathbf{M}}^{+}_{g,L_{bg},f,p} \geqslant 0, \dot{\mathbf{M}}^{-}_{g,L_{bg},f,p} \geqslant 0, \quad \forall L_{bg}, f, p, g \quad (56)$$

Two sets of balancing constraints, those at the origins and those at the destinations, are defined. For each type of resources/materials/products ($f \in F$), the sum of all out-going shipments from location g is equal to the available supply. The amount shipped out of $g \in G$ to a distention $g' \in G$ in layer L_{bg} is denoted by $\dot{\mathbf{M}}^{-}_{X_{g,g'},L_{bg},f,p}$. Therefore, the balancing constraint is (Eq.57);

$$\sum_{g'}^{N_G} \dot{\mathbf{M}}^{-}_{X_{g,g'},L_{bg},f,p} + \dot{\mathbf{F}}^{-}_{g,L_{bg},f,p} = \dot{\mathbf{M}}^{-}_{g,L_{bg},f,p} \qquad \forall L_{bg}, f, p, g, g \neq g' \quad (57)$$

The balancing constraint at the destination is much the same, except that the roles of g and g' are exchanged and the sum equals $\dot{\mathbf{M}}^{+}_{g',L_{bg},f,p}$ (Eq.58);

$$\sum_{g}^{N_G} \dot{\mathbf{M}}^{+}_{X_{g,g'},L_{bg},f,p} + \dot{\mathbf{F}}^{+}_{g',L_{bg},f,p} = \dot{\mathbf{M}}^{+}_{g',L_{bg},f,p} \qquad \forall L_{bg}, f, p, g', g \neq g' \quad (58)$$

The net import resources/materials/products of type f from outside the system boundaries in each layer is (Eq.59);

$$\dot{\mathbf{F}}_{L_{bg},f,p} = \sum_{g}^{N_G} (\dot{\mathbf{F}}^{+}_{g,L_{bg},f,p} - \dot{\mathbf{F}}^{-}_{g,L_{bg},f,p}) \qquad \forall L_{bg}, f, p \quad (59)$$

If $\sum_{p}^{N_p} \dot{\mathbf{F}}^{+}_{g,L_{bg},f,p} = 0$ or $\sum_{p}^{N_p} \dot{\mathbf{F}}^{-}_{g,L_{bg},f,p} = 0$, meaning the export/import of resources/materials/products f from/to location g is not beneficial. Consequently, the location of export/import gates and storage of $f \in F$ will be optimized through the proposed model.

The variable operating costs of the transportation as a function of distance and transport load is computed by Eq.60, and the total value will be added to Eq.2 and Eq.27;

$$\mathbf{COPL}_{L_{bg},f} = \sum_{p}^{N_P}\sum_{g}^{N_G}\sum_{g'}^{N_G}(\dot{COVL}_{L_{bg},f,p} \times dl_{X_{g,g'}} \times \dot{\mathbf{M}}^{+/-}_{X_{g,g'},L_{bg},f,p} \times \triangle p), \forall L_{bg}, f, g \neq g' \tag{60}$$

Where $dl_{X_{g,g'}}$ is the nearest path between locations g and g'. It can be estimated by using routing algorithms [33]. $\dot{COVL}_{L_{bg},f,p}$ [€/kWh/m] is the transport cost of resources/materials/products f in layer L_{bg}.

The Eq.61 computes the environmental impacts of shipments. The total impacts computed by Eq.62 and will be added to Eq.4 and Eq.33;

$$\mathbf{IL}_{L_{bg},f} = \sum_{g}^{N_G}\sum_{g'}^{N_G}(\dot{IL}_{L_{bg},f,p} \times dl_{X_{g,g'}} \times \dot{\mathbf{M}}^{+/-}_{X_{g,g'},L_{bg},f,p} \times \triangle p) \quad \forall L_{bg}, f, g \neq g' \tag{61}$$

$$\mathbf{IL} = \sum_{L_{bg}}^{N_{L_{bg}}}\sum_{f}^{N_F}\mathbf{IL}_{L_{bg},f} \tag{62}$$

$\dot{IL}_{L_{bg},f,p}$ refers to the reference environmental impacts of the transportation system for resource f in L_{bg}.
Table 6 summarizes the parameters and decision variables of the transportation model.

4.1. Aggregation of district's elements

Considering each individual location (for buildings, nodes and pipelines), in the proposed mixed integer optimization model, makes it difficult to solve. Therefore, an aggregation approach based on the *k-means* clustering method is proposed to present the district area with a macroscopic view by grouping locations into limited number of integrated zones. The proposed aggregation method is published in [34]

5. Illustrative example

The second test case presented in [21] is extended to demonstrate the networks design model. The goal is to supply the 4637 [GWh] annual heat, 954 [GWh] hot water and 870 [GWh] electricity demands of a city (450,000 inhabitants) with central plants via distribution networks. The city map with 13 corresponding integrated zones are presented in Figure 4. These 13 integrated zones are optimized by applying the aggregation approach [34]. Figure 5 refers to the hourly energy demand profiles of 450,000 inhabitants, solar irradiation and electricity price (eex.com 2011) of a typical year and 8 representative typical operating periods [23].

There are five candidate locations (S1, S2, S3, S4 and S5) for placing new central plants (Figure 4). Alternative conversion technologies, for supplying power and heat services, are; solar thermal, large natural gas, biomass and biogass boilers for the hot water and the steam productions, air wood dryer, biomethanation and air gasifiers for biogas production, natural gas and biogas engines and turbines, biogas and natural gas combined cycles, steam turbines, a heat pump integrated with wastewater treatment plant in location S1, and a municipal solid waste incinerator in location S3. The operation and the investment costs of conversion technologies are summarized in [21] and [20], which are estimated by using correlation given by [27].

The distance between the center of each two zones is estimated by considering the nearest path through the exist roads. The length of the local network in each integrated zone (dl_k) is computed by correlation 63, considering the land area (S_k), the number of buildings (n_b) and a topological factor (f). The value f = 0.23 has been identified from an existing network in Geneva [32]. The investment cost is calculated by Eq.53, and with $CIN1$ = 929 [€/m] and $CIN2$ = 23306 [€/m^3] [32]. The same correlation is applied to estimate the investment costs of pipelines between integrated zones, together with f^{loss}_{0,L_h} =10% [32].

$$dl_k \simeq 2 \times (n_b - 1) \times f \times \sqrt{\frac{S_k}{n_b}} \qquad \forall k \tag{63}$$

From the available data [35], 620000 [tons/year] are incinerated in the district. They are treated by the incinerator power plant, and the residual heat can be recovered through the global distribution networks. The available geothermal energy resources in 6 integrated zones are summarized in Table 7. According to [35], the biomass potential is 555 [GWh_{th}], but it may not be sufficient to satisfy the overall demands. Therefore, the natural gas and the electricity mix from the main grid are considered as potential imported resources.

The design and operation optimization of the system, including the networks' layout and the locations of centralized and decentralized plants, are performed with respect to three objectives; maximizing the system efficiency (**EFF**), minimizing the total investment and operating costs (**TAC**), and minimizing the environmental impacts ($\mathbf{M_{CO_2}}$) (Eq.64);

$$\max_{\mathbf{U_s},\mathbf{Y_s}} \{\mathbf{EFF}\}, \quad \min_{\mathbf{U_s},\mathbf{Y_s}} \{\mathbf{TAC}, \quad \mathbf{M_{CO_2}}\} \tag{64}$$

In the optimization model, the integer variables are defined in the master

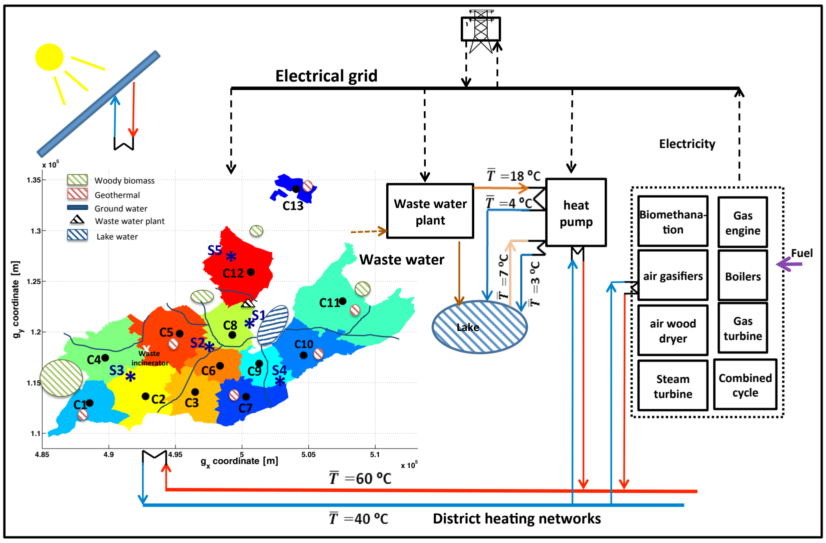

Figure 4: Network design illustrative example

optimization to select the type of conversion technologies in each location, while continuous variables are used for setting the $\mathbf{t_{CO_2}}$ weighing factor, the maximum available capacity of selected conversion technologies, the design flow velocity (ν [m/s]) and the supply and return temperatures of the distribution networks ($\mathbf{T}_{in}^{h/c}$ and $\mathbf{T}_{out}^{h/c}$). The network's layout and the operating schedule of selected conversion technologies are optimized in the slave optimization.

Figure 6 displays the first Pareto frontier resulting from multi-objective optimization model. It denotes trade-offs between the system efficiency (**EFF**: 34-75%), total annual costs (**TAC**: 1400-1950 [€/an/cap]) and environmental impacts per capita ($\mathbf{M_{CO_2}}$: 2.6-7.5 [tCO_2/an/cap]).

As an assumption, solution "B" (Figure 6) refers to the reference case, where the heat and hot water demands of each building are supplied by an

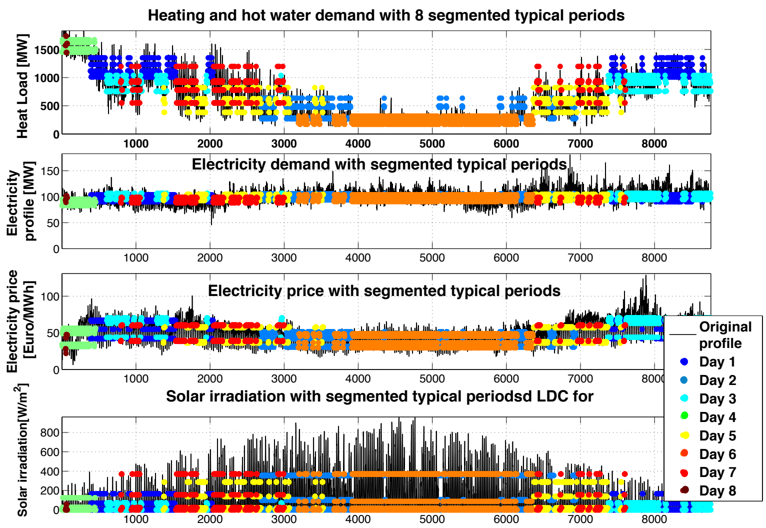

Figure 5: Solar irradiation, the heat and the electricity demand profiles with 8 representative segmented typical days

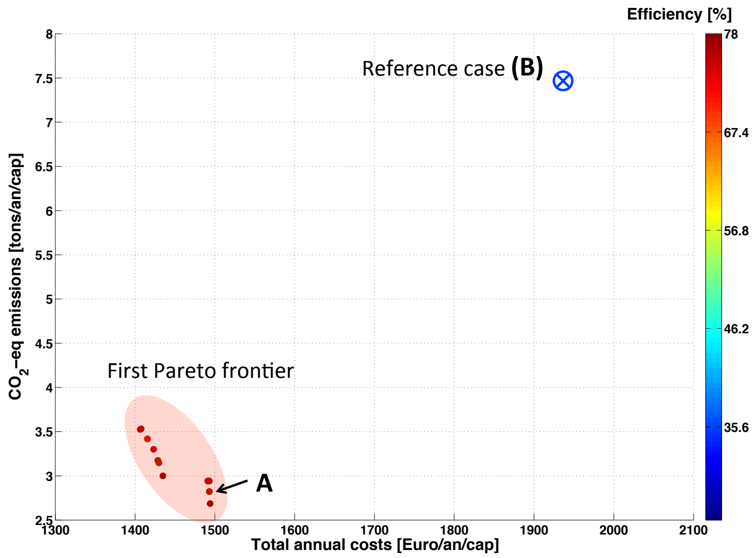

Figure 6: Multi objective optimization results - first Pareto frontier

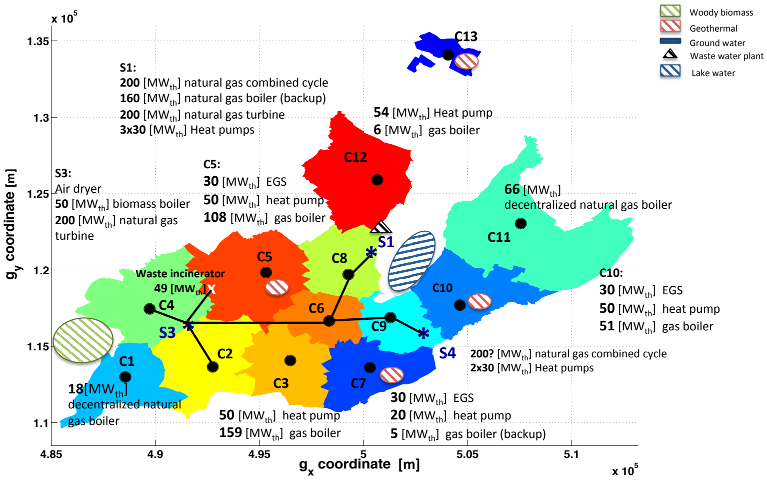

Figure 7: Network design illustrative example: Solution "A"

individual small gas boiler. Regarding the electricity consumption, 36% is supplied by the incinerator plant and the remaining demand is imported from the main grid.

Figure 6 points out that for the reference case the yearly CO_2 emissions per capita, the total annual costs per capita and the system efficiency are equal to 7.5 [tCO_2/an/cap], 1930 [€/an/cap] and 34% respectively. The total annual costs and the environmental impacts are relatively high, since decentralized boilers with 18 [TWh] natural gas consumptions are the only type of conversion technology in this solution.

The gap between the first Pareto frontier and the reference case (Solution "B") points out the thermo-environomic advantages of integration of local resources, centralized and decentralized technologies.

Among all solutions, configuration "A" (Figure 6) is selected for more details evaluation. The 75% efficiency in this solution is obtained due to the integration of co-generation technologies, endogenous resources (i.e. geothermal and ground water), and heat recovery from municipal solid waste incinerator. Decentralized boilers are chosen as optimal solution in integrated zones C1 and C11 due to relatively low heating demands and large distances between consumers. Meanwhile, the global distribution networks are selected between integrated zones C2, C4, C6, C8 and C9. Centralized enhanced geothermal systems, heat pumps and natural gas boilers with local distribution networks are chosen as optimal solutions in integrated zones C3, C5, C7, C10 and C12, without any exchange with the global networks. The extension of pipelines between locations is presented by Figure 7.

6. Conclusions

A systematic procedure including the transportation, the network design, process and energy integration techniques with simultaneous consideration of multi-period and multi-objectives aspects, for district energy system design and operation optimization is explained.

The network design model is introduced in order to optimize the networks' layout, configurations and locations of centralized and decentralized plants in an urban area. There is a trade off between centralized and decentralized solutions. In the developed model we consider not only the quantity of services but also the quality of heat requirements in terms of the temperature.

The illustrative example illustrates the proposed method helps decision makers to decide; which type and size of poly-generation technologies, centralized or decentralized, are best suited for the district, where in the district shall the equipment be located (geographically) and how resources and services should be distributed.

Table 1: Master optimization resume

Constraints		
TES		The thermo-economic simulation
EIO		The energy integration optimization
EE		The environomic evaluation
Parameters		
$F_s^{min/max}$	[kW]	Feasible ranges for size of conversion technologies
$T_{min/max}$	$[^oC]$	Feasible ranges of network's supply temperature
$T'_{min/max}$	$[^oC]$	Feasible ranges of network's return temperature
b_f^{max}	[kWh] or [kg]	Maximum availability of material of type f (i.e. products, waste, fuels)
Tax_{max}	$[€/tCO_2]$	Maximum value for environmental taxes
Variables		
$\mathbf{Y}_s \in \{0,1\}$		Binary decision variable for selection of conversion technologies, networks and resources
$\mathbf{U}_s$	[kW]	Continuous variables for sizing conversion technologies
$\mathbf{B}_f$	[kWh] or [kg]	Continuous variables for resource availability
$\mathbf{t_{CO_2}}$	$[€/tCO_2]$	Continuous variable for CO_2 taxes
$\mathbf{M_{CO_2}}$	$[tCO_2/\text{year}]$	Total environmental impacts in terms of CO_2 emissions
TAC	[€/year]	Total annual costs
EFF	[-]	Overall system's efficiency
$\mathbf{T}_{in/out}^{h/c}$	$[^oC]$	Continuous variables for supply and return temperatures of heating/cooling networks
		Other continuous variables for related operating parameters of equipment

Table 2: Thermo-economic simulation (TES) resume

Input data		
$T^{h/c}_{in/out}$	$[^oC]$	Networks' supply and return temperatures (initial and target states)
Y_s	[-]	Type of conversion technologies
U_s	[kW]	Size of conversion technologies
		Related operating parameters of various technologies
Variables		
$\mathbf{t}^{in/out}_{s,p}$, $\dot{\mathbf{Q}}^{+/-}_{g,L_h,s_{j/i},p}$	$[^oC]$,[kW]	Thermo dynamic attributes of subsystem s at time step p
$\dot{\mathbf{I}}_{s,p}$	$[tCO_2/s]$	The reference environmental impacts of subsystem s
$\dot{\mathbf{E}}^{+/-}_{g,L_b,s_e,p}$	[kW]	The reference subsystem's power
$\dot{\mathbf{M}}^{+/-}_{g,L_b,s_f,p}$	[kW] or [kg/s]	The reference inlet and outlet materials (i.e. water, products, waste, fuels)
$\mathbf{U}^{min/max}_s$	[-]	Feasible ranges of subsystem's utilization
$\mathbf{C}_s$		The reference **linear** operating expenses including: $\mathbf{CO\dot{V}1}_{s,p}$ [€/s], $\mathbf{CO\dot{V}2}_{s,p}$ [€/s], $\mathbf{COF1}_s$ [€/year], $\mathbf{COF2}_s$ [€/year], $\mathbf{CI}_s$ [€]

Table 3: Slave energy integration optimization resume

Parameters		
$C\dot{O}V1/2_{s,p}$	[€/s]	Linear terms of hourly operating costs
$COF1/2_s$	[€/year]	Linear terms of yearly maintenance costs
Δp	[s]	Duration of time step p
t_{CO_2}	[€/tCO_2]	Emissions taxes
U_s^{min}	[-]	Part load utilization of subsystem s
U_s^{max}	[-]	Maximum utilization of subsystem s
$\dot{Q}^{-}_{g,L_h,s_i,k,p}$	[kW]	The reference heat requirement of cold stream i
$\dot{Q}^{+}_{g,L_h,s_j,k,p}$	[kW]	The reference heat available of hot stream j
$\dot{E}^{-/+}_{g,L_{bl}/L_{bg},s_e,p}$	[kW]	The reference electricity consumption/production of subsystem s
$\dot{M}^{-/+}_{g,L_{bl}/L_{bg},s_f,p}$	[kW] or [kg/s]	The reference resource consumption/production of type f
$B_{g,L_{bl}/L_{bg},f,p}$	[kWh] or [kg]	Maximum resource availability of type f
$m^{grid}_{I,L_{bg}}$	[tCO_2/kWh]	The environmental impacts of the electricity import from the grid in layer L_{bg}
$m_{f,I}$	[tCO_2/kWh] or [tCO_2/kg]	The environmental impacts of material f (i.e. products, waste, fuels)
$\dot{I}_{s,p}$	[tCO_2/s]	The overall emissions of subsystem s for utilization of reference size
Variables		
$\mathbf{y}_{s,p}$	[-]	Binary variables for activating subsystem s at time step p
$\mathbf{u}_{s,p}$	[-]	Continuous variable for utilization level of subsystem s at time p
$\mathbf{u}_s$	[-]	Maximum utilization level of subsystem s
$\dot{\mathbf{R}}_{g,L_h,k,p}$	[kW]	The residual heat from the temperature interval k of layer L_h in location g
$\dot{\mathbf{E}}^{+/-}_{grid,L_{bg},p}$	[kW]	The electricity export/import from the grid
$\dot{\mathbf{F}}_{g,L_{bl},f,p}$	[kW] or [kg/s]	The local material consumption of type f (i.e. water, products, waste, fuels) in local layer
$\dot{\mathbf{F}}_{L_{bg},f,p}$	[kW] or [kg/s]	The import/export material of type f (i.e. water, products, waste, fuels) in global layer
$\dot{\mathbf{I}}_p$	[tCO_2/s]	The total emissions at time step p
$\dot{\mathbf{I}}_{grid,p}$	[tCO_2/s]	The emissions of import/export electricity from the grid
$\dot{\mathbf{I}}_{f,p}$	[tCO_2/s]	The emissions of import material f (i.e. water, products, waste, fuels), which is imported/exported from/to abroad or local/global storage systems or indigenous resources, at time step p

Table 4: Typical cost of network pipes, for diameters between 25mm and 300mm and f^{loss}_{0,L_h} =10% [32].

pipe diameter[mm]	25	40	50	65	80	100	125	150	200	250	300
pipe cost[10^3CHF/m]	0.95	1	1.2	1.25	1.35	1.47	1.6	1.75	2	2.5	3

Table 5: The network model's decision variables and parameters

Parameters		
$N_{g,g'}$	[-]	pipeline from location g to g'
$g_{x/y}$	$[m]$	geographical coordinates of each location
$\dot{Q}^{+/-}_{N_{g,g'},L_h,k'',p}$	[kW]	the reference heat transfer in pipeline $N_{g,g'}$
$\dot{Q}^{loss,0}_{N_{g,g'},L_h,k''}$	[kW]	the linear term of the reference heat loss in pipeline $N_{g,g'}$
$f^{loss}_{L_h,k''}$	[-]	the heat loss factor
f^{loss}_{0,L_h}	[-]	the reference heat loss factor
T_{gnd}	$[^oC]$	the ground temperature
ν	[m/s]	the nominal velocity of the fluid
ρ	$[kg/m^3]$	the density of the fluid in the pipeline
Cp	$[kJ/kg/^oC]$	the specific heat capacity of the fluid
$dl_{N_{g,g'}}$	$[m]$	the length of the pipeline $N_{g,g'}$
IN_{L_h}	$[tCO_2/m^3]$	the environmental impacts of pipeline in layer L_h
$COFN1_{L_h}$	[€$/m$]	linear terms of network's fixed maintenance and operating costs
$COFN2_{L_h}$	[€$/m^3$]	linear terms of network fixed operating costs
$CIN1_{L_h}$	[€$/m$]	linear terms of network investment costs
$CIN2_{L_h}$	[€$/m^3$]	linear terms of network investment costs
$U^{min/max}_{N_{g,g'},L_h}$	[-]	the minimum and the maximum feasible utilization level of pipeline
$\dot{E}1/2_{N_{g,g'},L'_{bg}}$	[kW]	the linear terms of the reference pumping power through the networks pipeline
Variables		
$\dot{\mathbf{Q}}^{+}_{N_g,L_h,k'',p}$	[kW]	the available heat comes from other locations to location $g \in G$
$\dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p}$	[kW]	the residual heat which transfers from location $g \in G$
$\mathbf{u}_{N_{g,g'},L_h,p}$	[-]	the utilization level of each pipeline $N_{g,g'}$ in time p
$\mathbf{u}_{N_{g,g'},L_h}$	[-]	the maximum utilization level of each pipeline $N_{g,g'}$
$\mathbf{d}_{N_{g,g'},L_h}$	$[m]$	the diameter of pipeline $N_{g,g'}$
$\mathbf{COFN}_{L_h}$	[€/year]	the total fixed operating costs of the network
$\mathbf{COVN}_{L_h}$	[€/year]	the total variable operating costs of the network
$\mathbf{CIN}_{L_h}$	[€]	the total investment cost of the network
$\mathbf{IN}_{L_h}$	[tCO_2/year]	the environmental impacts of network
$\dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h}$	[kW]	the maximum heat load which is transferred through the pipeline $N_{g,g'}$
$\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p}$	[kW]	the Network heat losses
$\mathbf{y}_{N_{g,g'},L_h}$	[-]	denotes the existence of the pipeline $N_{g,g'}$
$\mathbf{y}_{N_{g,g'},L_h,p}$	[-]	a binary variable for activating the pipeline $N_{g,g'}$ at time p
$\dot{\mathbf{E}}_{N,L'_{bg},p}$	[kW]	pumping power through the networks pipeline

Table 6: The logistics model's decision variables and parameters

Parameters		
$X_{g,g'}$	[-]	connection between locations g and g'
$g_{x/y}$	[m]	geographical coordinates of each location
$dl_{N_{g,g'}}$	[m]	the distance between locations g and g'
$\dot{M}^{+/-}_{g,L_{bg},s_f,p}$	[kW] or [kg/s]	the reference production/consumption of material f in subsystem s
$\dot{IL}_{N_{g,g'}}$	[tCO_2/kWh/m]	the environmental impacts of the transportation system
$CO\dot{V}L_{L_{bg},f,p}$	[€/kWh/m]	linear terms of variable operating cost of the transportation system
Variables		
$\dot{\mathbf{M}}^{+/-}_{X_{g,g'},L_{bg},f,p}$	[kW] or [kg/s]	the export/import material between locations g and g'
$\dot{\mathbf{F}}^{+/-}_{g,L_{bg},f,p}$	[kW] or [kg/s]	the material export/import from outside the system boundaries in location g
$\dot{\mathbf{F}}_{L_{bg},f,p}$	[kW] or [kg/s]	the total net material f import from outside the system boundaries
$\dot{\mathbf{M}}^{+/-}_{g,L_{bg},f,p}$	[kW] or [kg/h]	the total export/import material f in location g
$\mathbf{COPL}_{L_{bg},f}$	[€/year]	the operating cost of the materials' transportation
$\mathbf{IL}_{L_{bg},f}$	[tCO_2/year]	the environmental impacts of the materials' transportation

Table 7: Geothermal energy availability in each iterated zone

Integrated zone	C1	C5	C7	C10	C11	C13
available power from the geothermal source [MW]	24	35	35	36	36	24

Nomenclature

$MILP$	mixed integer linear programming
MOO	multi objective optimisation
TES	The thermo-economic simulation
EIO	The energy integration optimization
EE	The environomic evaluation
$F_s^{min/max}$	Equipment's feasible ranges
$T_{min/max}$	Feasible ranges of network's supply temperature
$T'_{min/max}$	Feasible ranges of network's return temperature
b_f^{max}	Maximum availability of fuel type f
Tax_{max}	Maximum value for environmental taxes
$\mathbf{Y}_s$	Binary decision variable for selection of conversion technologies, networks and resources
$\mathbf{U}_s$	Continuous variables for sizing conversion technologies
$\mathbf{B}_f$	Continuous variables for resource availability
$\mathbf{t_{CO_2}}$	Continuous variable for CO_2 taxes
$\mathbf{T}_{in/out}^{h/c}$	Continuous variables for supply and return temperatures of heating/cooling networks
$\mathbf{M_{CO_2}}$	Total environmental impacts in terms of CO_2 emissions
TAC	Total annual costs
EFF	Overall system's efficiency
Y_s	Type of conversion technologies
U_s	Size of conversion technologies
$\dot{\mathbf{Q}}_{g,L_h,s_{j/i},p}^{+/-}$	Thermo dynamic attributes (heat) of subsystem s
$\mathbf{t}_{s,p}^{in/out}$	Thermo dynamic attributes (temperature) of subsystem s
$\dot{\mathbf{I}}_{s,p}$	Subsystem's emissions
$\dot{\mathbf{E}}_{g,L_b,s_e,p}^{+/-}$	Subsystem's power
$\dot{\mathbf{M}}_{g,L_b,s_f,p}^{+/-}$	Inlet sources and outlet products

$\mathbf{U}_s^{min/max}$	Feasible ranges of subsystem's utilization
$\mathbf{C}_s$	Linear operating expenses
$\mathbf{CO\dot{V}1/2}_{s,p}$	variable operating expenses
$\mathbf{COF1/2}_s$	Fixed operating expenses
$\mathbf{CI}_s$	Investment cost
$CO\dot{V}1/2_{s,p}$	Linear terms of hourly operating costs
$COF1/2_s$	Linear terms of yearly maintenance costs
Δp	duration of time step p
t_{CO_2}	emissions taxes
U_s^{min}	part load power of subsystem s
U_s^{max}	max power of subsystem s
$\dot{Q}^-_{g,L_h,s_i,k,p}$	the reference heat requirement of cold stream i
$\dot{Q}^+_{g,L_h,s_j,k,p}$	the reference heat available of hot stream j
$\dot{E}^{-/+}_{g,L_{bl}/L_{bg},s_e,p}$	the reference electricity consumption / production of subsystem s
$\dot{M}^{-/+}_{g,L_{bl}/L_{bg},s_f,p}$	the reference resource consumption/production of type f
$B_{g,L_{bl}/L_{bg},f,p}$	maximum resource availability of type f
m_I^{grid}	the environmental impacts of electricity import from the grid
$m_{f,I}$	the environmental impacts of fuel f
$\dot{I}_{s,p}$	the overall emissions of subsystem s
$\dot{Q}^-_{g,L_h,s'_i,k',p}$	the reference heat discharging
$\dot{Q}^+_{g,L_h,s'_j,k',p}$	the reference heat charging
$V_{s'}^{max}$	the maximum feasible volume of storage s'
ρ	the density of the considered storage fluid
Cp	the specific heat capacity
$\mathbf{y}_{s,p}$	binary variables for activating subsystem s at time p
$\mathbf{u}_{s,p}$	continuous variable for utilization level of subsystem s at time p
$\mathbf{u}_s$	maximum utilization level of subsystem s

$\dot{\mathbf{R}}_{g,L_h,k,p}$	the residual heat from the temperature interval k
$\dot{\mathbf{E}}^{+/-}_{grid,L_{bg},p}$	the electricity export / import from the grid
$\dot{\mathbf{F}}_{g,L_{bl},f,p}$	the import fuel of type f in local layer
$\dot{\mathbf{F}}_{L_{bg},f,p}$	the import fuel of type f in global layer
$\dot{\mathbf{I}}_p$	the total emissions at time p
$\dot{\mathbf{I}}_{grid,p}$	the emissions of import/export electricity from the grid
$\dot{\mathbf{I}}_{f,p}$	the emissions of import fuel f
$\mathbf{u}'_{s',k',j,p}$	continuous variable for the charging rate of storage s'
$\mathbf{u}'_{s',k',i,p}$	continuous variable for the discharging rate of storage s'
$\mathbf{V^0}_{s',t_{k'}}$	the initial volume of each level $t_{k'}$ of storage s'
$\mathbf{V}_{s',t_{k'},p}$	the volume $[m^3]$ of each level during time step p of storage s'
$\mathbf{V}_{s'}$	the total volume $[m^3]$ of each storage tank s'
$\mathbf{y}_{s',p}$	a binary variable for activating the storage subsystem s' in time p
$\mathbf{y}_{s'}$	a continuous variable which denotes the existence of storage s'
$\mathbf{COP}_{s'}$	the total operating cost of storage s'
$\mathbf{CI}_{s'}$	the total investment cost of storage s'
$\mathbf{I}_{s'}$	the environmental impacts of storage s'
$N_{g,g'}$	pipeline from location g to g'
$g_{x/y}$	geographical coordinates of each location
$\dot{Q}^{+/-}_{N_{g,g'},L_h,k'',p}$	the reference heat transfer of pipeline $N_{g,g'}$
$\dot{\mathbf{Q}}^{loss}_{N_{g,g'},L_h,k'',p}$	the heat loss of pipeline $N_{g,g'}$
$\dot{Q}^{loss,0}_{N_{g,g'},L_h,k''}$	the linear term of heat loss of pipeline $N_{g,g'}$
$f^{loss}_{L_h,k''}$	the heat loss factor
f^{loss}_{0,L_h}	the reference heat loss factor
T_{gnd}	the ground temperature
ν	the nominal velocity of fluid

ρ	the density of the fluid in the pipeline
Cp	the specific heat capacity
$dl_{N_{g,g'}}$	the length of the pipeline $N_{g,g'}$
$IN_{N_{g,g'}}$	the environmental impacts of pipeline $N_{g,g'}$
$COFN1_{L_h}$	linear terms of network operating cost
$COFN2_{L_h}$	linear terms of network operating cost
$CIN1_{L_h}$	linear terms of network investment cost
$CIN2_{L_h}$	linear terms of network investment cost
$U^{min/max}_{N_{g,g'},L_h}$	the minimum and the maximum feasible utilization level of pipeline
$\dot{E}1/2_{N_{g,g'},L'_{bg}}$	the linear terms of the reference pumping power through the networks pipeline
$\dot{\mathbf{Q}}^{+}_{N_g,L_h,k'',p}$	the available heat comes from other locations to location $g \in G$
$\dot{\mathbf{Q}}^{-}_{N_g,L_h,k'',p}$	the residual heat which transfers from location $g \in G$
$\mathbf{u}_{N_{g,g'},L_h,p}$	the utilization level of each pipeline $N_{g,g'}$ in time p
$\mathbf{u}_{N_{g,g'},L_h}$	the maximum utilization level of each pipeline $N_{g,g'}$
$\mathbf{d}_{N_{g,g'},L_h}$	the diameter of pipeline $N_{g,g'}$
$\mathbf{COFN}_{L_h}$	the total fixed operating costs of the network
$\mathbf{COVN}_{L_h}$	the total variable operating costs of the network
$\mathbf{CIN}_{L_h}$	the total investment cost of network
$\mathbf{IN}_{L_h}$	the environmental impacts of network
$\dot{\mathbf{Q}}^{max}_{N_{g,g'},L_h}$	the maximum heat load which is transferred through the pipeline $N_{g,g'}$
$\dot{\mathbf{E}}_{N,L'_{bg},p}$	pumping power through the networks pipeline
$\mathbf{y}_{N_{g,g'},L_h}$	a binary variable which denotes the existence of pipeline $N_{g,g'}$
$X_{g,g'}$	conection between locations g and g'
$g_{x/y}$	geographical coordinates of each location
$dl_{N_{g,g'}}$	the distance between locations g and g'
$\dot{M}^{+/-}_{g,L_{bg},s_f,p}$	the reference production/consumption of fuel f in subsystem s

$\dot{IL}_{N_{g,g'}}$ the environmental impacts of the transportation system

$\dot{COVL}_{L_{bg},f,p}$ linear terms of variable operating cost of the transportation system

$\dot{\mathbf{M}}^{+/-}_{X_{g,g'},L_{bg},f,p}$ the export/import fuel between locations g and g'

$\dot{\mathbf{F}}^{+/-}_{g,L_{bg},f,p}$ the fuel export/import from abroad in location g

$\dot{\mathbf{F}}_{L_{bg},f,p}$ the total net fuel import from abroad

$\dot{\mathbf{M}}^{+/-}_{g,L_{bg},f,p}$ the total export/import fuel in location g

$\mathbf{COPL}_{L_{bg},f}$ the operating cost of the transportation

$\mathbf{IL}_{L_{bg},f}$ the environmental impacts of the transportation

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Appendix A. Supplementary material

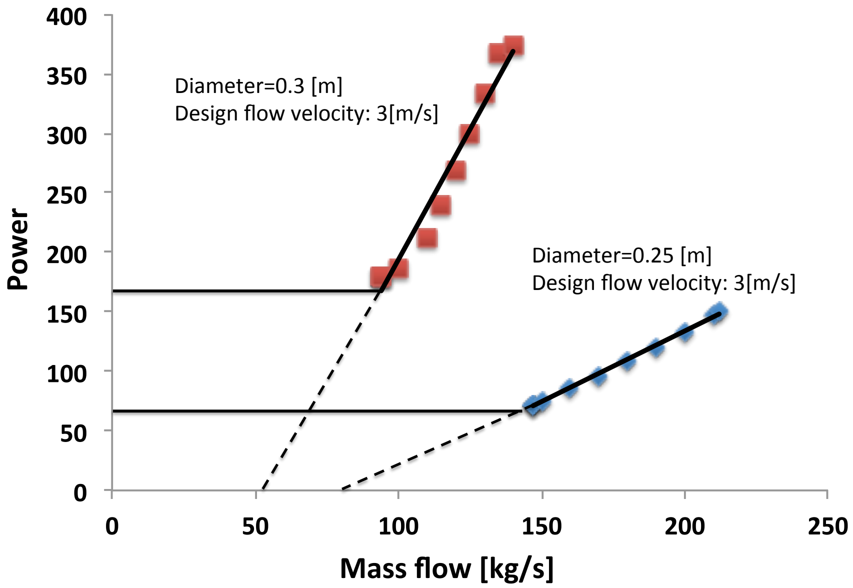

Figure S1: Distribution network pumping power as a function of the mass flow for diameters 250 mm and 300 mm.