A SUPPLY/DEMAND DECISION MAKING-TOOL FOR THE REGIONAL COORDINATED PLANNING OF THERMAL NETWORKS

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ABSTRACT

The development of urban areas by densification of the existing urban infrastructure and setting up of new dwellings raises the question of spatial and temporal distribution of energy supplies to provide thermal comfort. Urban development projects are indeed not necessarily coordinated and may unexpectedly appear, either through new building projects or by opportunistic study of key area, or by motivation of public or private actors.

The aim of the proposed methodology is to generate optimum scenarii matching, in a long term perspective, the load and temperature levels of heat supply sources and thermal demand of urban areas. It uses energy integration techniques to simulate the thermal energy portfolios, taking into consideration the possibility to increase the supply temperature levels of energy supply sources using heat pumps. The results from simulation are expressed as thermal load curves and a network-diagram connecting urban areas, energy supply sources and heat pumps.

Although many points of view might be considered for the correlation between urban thermal energy supply and demand, some criteria, such as exergy losses, CO_2 emissions, costs and the amount of renewable energy, are strictly quantitative and can be optimized by mathematical programming.

The associated tool is validated on a simple case study and applied for the regional coordinated thermal energy planning of an urban area in Geneva, using six temporal horizon up to year 2100.

Keywords: urban simulation, energy integration, thermal networks, multi-period optimisation

INTRODUCTION

Given the growing demand of heterogeneous powers and temperatures, the establishment of a territorial-coordinated strategic vision 2050-2100 of the thermal energy supply requires the development of a decision-making tool based on the simulation of spatial and temporal evolution of the urban energy system. The method contributes to the better integration of district heat network, renewable energy sources and waste heat in correlation with the evolution of urban demand.

METHODOLOGY

The developed methodology is based on current and future urban hourly heat-temperature demand profiles, generated either with a typological approach [1] or using more advanced urban simulation software, such as CitySim [2]. The initial urban demand is updated, horizon by horizon, using refurbishment rates and considering new developments, in order to predict the evolution of the heat and temperature demand. The sizing temperatures of the heating demands are set to 80/65°C for existing buildings, 65/45°C for refurbished ones and 45/20°C for the new ones.

Given the urban energy demand and the boundaries of the energy supply loads, the use of energy integration techniques [3, 4], with spatial [5] and temporal restriction, optimally allocates heat loads throughout urban zones considering the temperatures constraints. The method's originality lies in the use of temporal horizon in which the operational planning of the heat supply [6] are performed, considering the possibility of heat sources temperature upgrades. This method linking together time horizons, brings the long term vision needed to perform the coordinated planning of thermal network.

The decision-making process relies on parametric multi-objective optimisation [7] to identify feasible alternatives. A first loop generate a fixed number of sub-optimal solutions between the min. and max. of a single objective and a second one repeats the procedure for each objective, namely exergy losses of heat exchanges, CO_2 emissions and operating costs. The outcome is a cloud of points with a "Pareto front" showing the trade-off between the objectives.

MODEL

The model is composed of streams sets (s), either variable supply or constant demand, geographical zone (z), temporal horizon (h) and time steps (t) with a distinction between operational and sizing conditions.

Annual load profile are made of ordered time series of heat streams $(Q,T_{in},T_{out},\Delta T_{/2})[z,t,h]$ with fixed inlet (T_{in}), outlet (T_{out}) and minimum temperature difference ($\Delta T_{/2}>0$) of the heat exchanges. Streams (s) are grouped within zones (Z_s), temporal horizon (H_s) and units (U_s) which comprise heat supply sources, demand and heat pumps. The heat load (Q) of heat supply is modulated by a multiplication factor ($f_s[z,t,h]$). In a same unit, all the streams share a common multiplication factor ($f_u[z,t,h] = f_s[z,t,h]$, $\forall$ t, $s \in U_s$, Z_s, H_s) which is bounded by user defined limits ($F_{min}[u]$ and $F_{max}[u]$). Moreover binary shut on/off variables (y_{uzth}) allow to set time and space restrictions to the heat supply distribution.

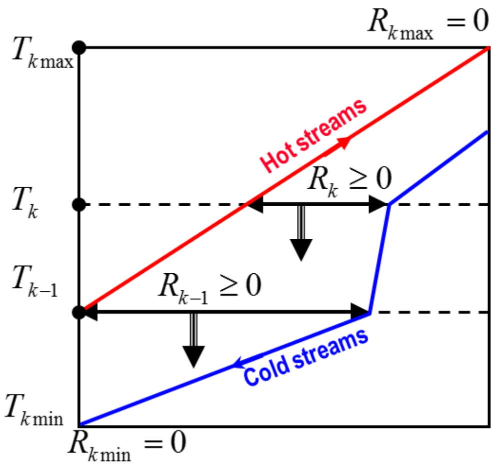
Energy balance

Heat supply ($T_{out}>T_{in}$) and demand ($T_{out}>T_{in}$) streams define variable hot, respectively fixed cold streams with flow ($Mc_p=Q[s,t]/(T_{in}[s,t]-T_{out}[s,t])$).

The mathematical mixed integer linear program (MILP) solves, in each zone (z) and for every time horizon (h), the energy balance (2) on each temperature interval (T_k,T_{k-1}) derived from all the streams.

$$\begin{aligned}\forall z,t,h,T_k : R_k[z,t,h,T_k] = \\ \sum_{s\in hot,T_{out}[s,t]\geq T_k} f_s[s,z,t,h]\cdot Mc_p[s,t]\cdot\left(T_{in}[s,t]-T_{out}[s,t]\right) - \sum_{s\in cold,T_{in}[s,t]\geq T_k} f_s[s,z,t,h]\cdot Mc_p[s,t]\cdot\left(T_{out}[s,t]-T_{in}[s,t]\right) \\ + \sum_{s\in hot,T_{out}[s,t]<T_k,T_{in}[s,t]\geq T_k} f_s[s,z,t,h]\cdot Mc_p[s,t]\cdot\left(T_{in}[s,t]-T_k\right) - \sum_{s\in cold,T_{in}[s,t]\leq T_k,T_{out}[s,t]\geq T_k} f_s[s,z,t,h]\cdot Mc_p[s,t]\cdot\left(T_{out}[s,t]-T_k\right)\end{aligned} \tag{2}$$

The series of positive residuals $R_k(z,t,h,T_k)$ define, for each time step (t), a heat cascade schematically depicted in Figure 1, which ensures that the thermal exchanges between hot (offer) and cold (demand) streams are all made with a positive temperature difference. The continuous variables of this problem are the residuals (R_k), the multiplying factor (f_s and f_u) of stream (s) and unit (u).



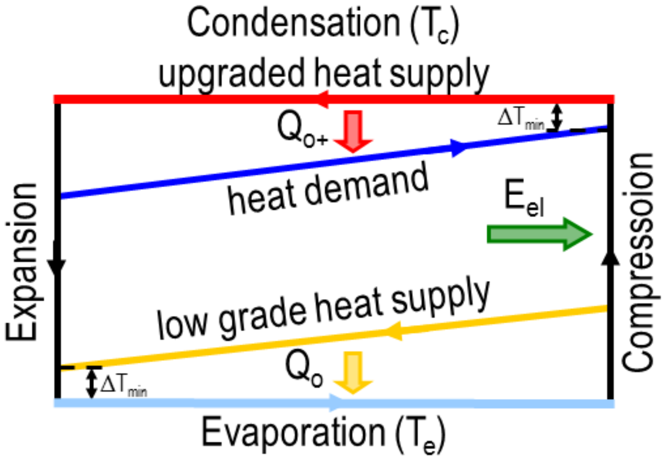


Figure 1: Schema of the heat cascade with balanced supply stream on the top.

Figure 2: Schema of heat pump integration for the upgrade heat supply temperature.

The closure of the global thermal balance, meaning the sum of hot streams equals the sum of cold streams, is achieved with the bounds constraints $R_k=0$ at the two ends of the heat cascade, at $\max_k(T_k)$ and $\min_k(T_k)$.

Temperature upgrade

The temperature levels of low grade heat supply sources may be upgraded using heat pumps (HP) which add a new electric demand and two streams: a new high grade heat supply above the condensation level (T_c) and a new demand at evaporation levels (T_e), just under the upgraded heat supply (Figure 2). These two new streams are linked together by a common multiplication factor (f_u), which preserves the ratio of the streams and represents the sizing factor of the HP unit (u).

The coefficient of performance ($COP= \eta_{COP} \cdot COP_{th}$) is computed based on the theoretical cycle of the HP ($COP_{th}=T_c/(T_c-T_e)$) using an efficiency factor (η_{COP}), of typically 0.4 for decentralized HP and 0.6 for more efficient centralized HP. The relation between the heat (Q_e) withdraws from upgraded heat supply and the amount of heat (Q_c) delivered at the higher temperature (T_c) is given by ($Q_c=Q_e \cdot (1+1/COP)$), and the amount of required electricity by ($E_{el}=Q_e/COP$).

VALIDATION CASE

The network-diagrams of Figure (3) show the heat load distribution minimizing the CO_2 emissions of three supply sources (Table 3) to two urban zones during horizon 2016-2030 (14 years). It is shown that 3'219 GWh are distributed to zones "PAV" and 1093 GWh to "Semailles" with a heat supply share of 2'948.2 GWh (Backup gas boiler at 120/90 °C), 1'028 GWh (Waste heat from Cheneviers at 120-106/75 °C) and 180.3 GWh (Waste heat from ZIPLO at 30/15 °C).

The optimal integration of heat pump allows to upgrade 165.7 GWh from "ZIPLO" adding 321.2 GWh to "Cheneviers" (1'028 GWh) which can then redistribute 1349.2 GWh to the urban zones. Using the heat pump maximises the usage of the low temperature and low emission "ZIPLO" heat source.

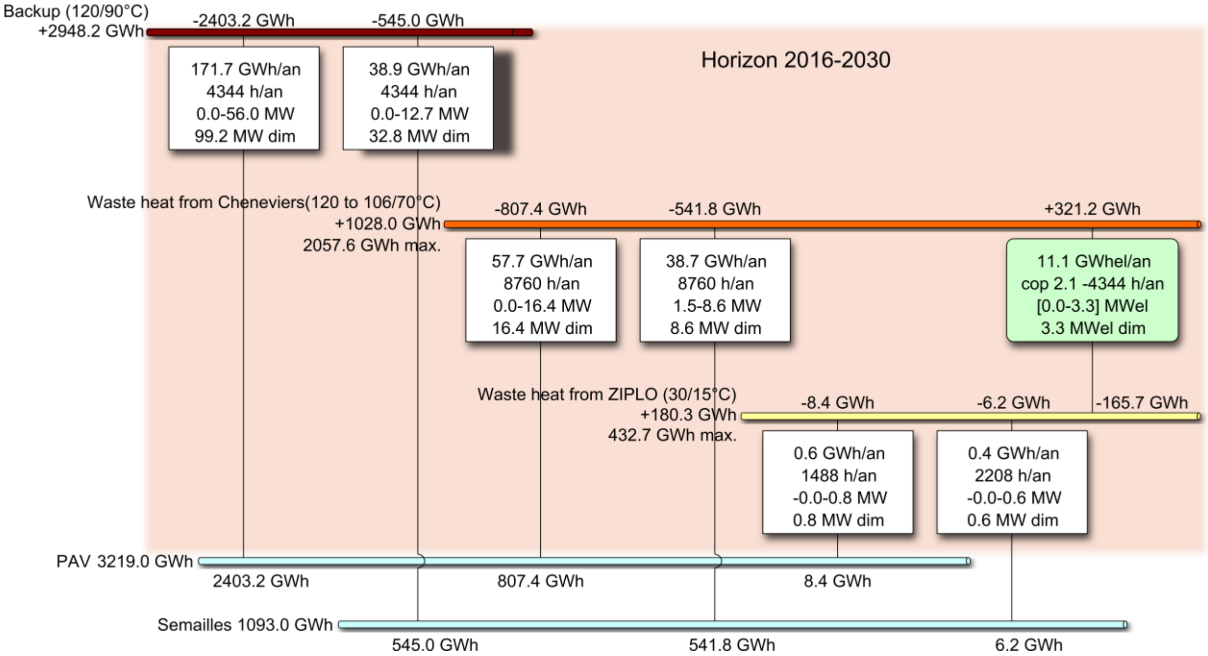


Figure 3: Network diagram of the validation case with heat upgrade.

The indicators, reported in Table 1 are well estimated with monthly time step, but daily simulation, with 12 typical days within a year, is required for the accurate detection of temperature upgrades and charges.

Minimisation of CO_2 emissions	**Indicators**				**Supply load [GWh/year]**				
	Exergy losses [GWh/year]	CO_2 emissions [gCO_2/kWh]	Operating cost [cts/kWh]	ReS share [%]	ZIPLO	Cheneviers	Backup	PAC Th.	PAC El.
Annual	48.3	103.1	8.6	47.0	30.9	147.0	102.6	58.4	27.5
Seasonal	44.0	169.5	8.7	27.2	18.6	84.5	191.6	27.4	13.3
Monthly	**43.1**	**183.9**	**8.7**	**22.9**	**12.9**	**73.4**	**210.6**	**22.9**	**11.1**
Daily (12x24h)	41.6	184.5	8.6	22.0	11.0	70.6	212.2	20.6	10.0

Table 1: Indicators and supply load distribution with different simulation's time steps.

CASE STUDY

The case study comprises nine geo-localized heat supply sources and nine urban zones (Figures 4 and 5), representing more than 500 hectares of heated surface. Daily, monthly and seasonal simulations are performed, up to horizon 2100, using six temporal horizon. A refurbishment rate of 1% per year is applied to the existing building stock. The result of the minimization of exergy losses, using monthly time step without heat upgrade, are shown in Table 2.

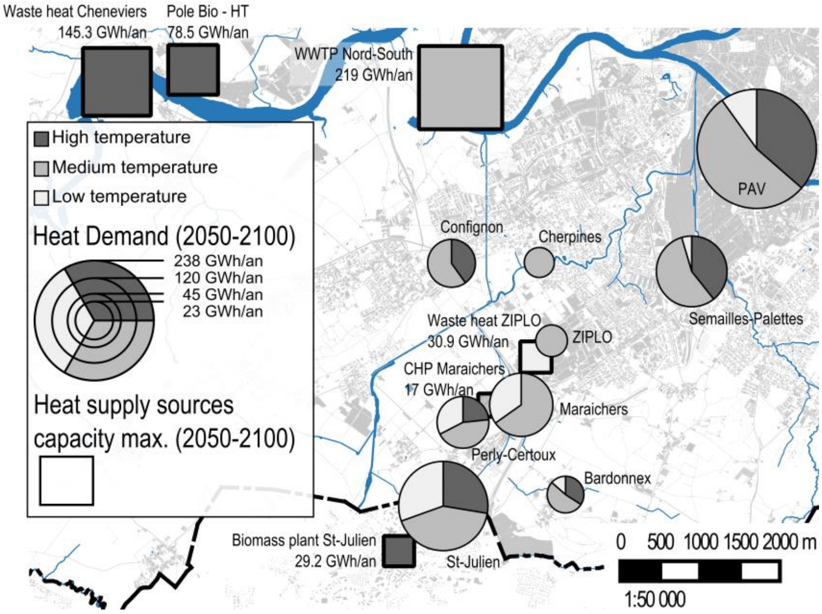


Figure 4: Map of heat supply (square) and demand (point).

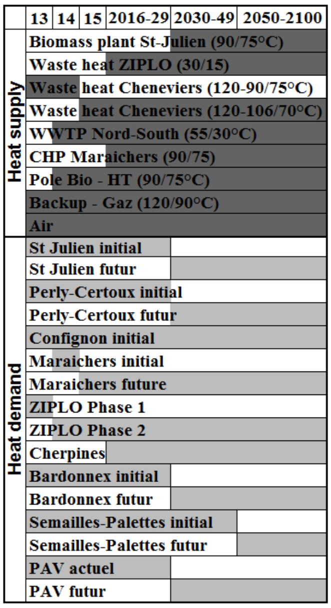


Figure 5: Gantt diagram.

Minimisation of exergy losses	Time horizon duration	**Indicators** Exergy losses	CO$_2$ emissions	Operating cost	ReS share	**Supply load [GWh/year]** Backup	Biomass plant St-Julien	CHP Maraichers	Waste heat Cheneviers	Pole Bio	Waste heat ZIPLO	WWTP Nord-South	Total
2013-2014	1	58.67[GWh/year]	54.17 [g/kWh]	7.68 [cts/kWh]	21.50 [%]	457.3			120.7				578.0
2014-2015	1					283.8			67.7	55.0		153.1	559.6
2015-2016	1					308.4			41.8	67.6		160.3	578.1
2016-2030	14					265.3	25.4	14.3	37.3	65.3	25.1	164.5	597.2
2030-2050	20					310.4	29.2	15.7	37.9	64.0	27.1	167.0	651.3
2050-2100	50					277.2	25.4	14.3	37.7	64.4	26.4	166.1	611.5
2013-2100	87					285.4	25.4	14.1	39.0	63.6	25.4	163.9	617.0

Table 2: Minimization of the exergy losses using monthly time step, without heat upgrade.

DISCUSSION

The results show that, with the given refurbishment rates and increase of the building stock, the heat demand is expected to grow between 2014 (578 GWh/year) and 2050 (650 GWh/year), with peak in 2030-2050. By the horizon 2050-2100, the demand will fall back to the level of 2016-2030 (600 GWh/year). Moreover, at least 45% of the studied urban area will not be covered by the planned network infrastructures, due to integration of backup technologies at a minimum level of 277.2 GWh/an (see table 2). However, the use of decentralized extra heat is expected to be reduced by more than one-third up to 2100, due to the lowering of heating temperature and the confluence of new supply capacities. Moreover, due to excess of heat supply in summer (e.g waste incineration plant "Cheneviers" 2013-2014, see Table 2 & Figure 4), the full potential of thermal sources will require the implementation of seasonal thermal storages. It also has been found that, even if the use of twelve typical days of 24h within a year gives suitable simulation results, the definition of about seven typical day [8] would generate even faster results with a more accurate placement of HPs.

CONCLUSION AND PERSPECTIVES

The heat supply/demand multi-period and multi-horizon decision-making tool is demonstrated at the scale of dwellings up to regional urban areas. By optimal supply/demand correlation, it helps energy planners to prepare future infrastructure investment and policy options to organize the energy transition with the best compromise between operation cost, technical efficiency and low CO_2 emission. The method is forecasting the decreases of temperature in the urban environment which, in turn, reveal the potential of renewable energy sources and reduce investments and heat losses of heat distribution networks. Furthermore, the integration of intermittent renewable sources, such as solar thermal energy, as well as the interaction with cold requirements with temperature downgrade for cooling, can be fulfilled with the proposed approach.

However, the integration of thermal storage will require new programming strategies and a supplementary module for the design of the thermal network [1] would provide decision-makers with the distribution costs needed to make the best investment choices.

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