Thermo-Economic Evaluation of a Virtual District Heating Network Using Dynamic Simulation

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Abstract:

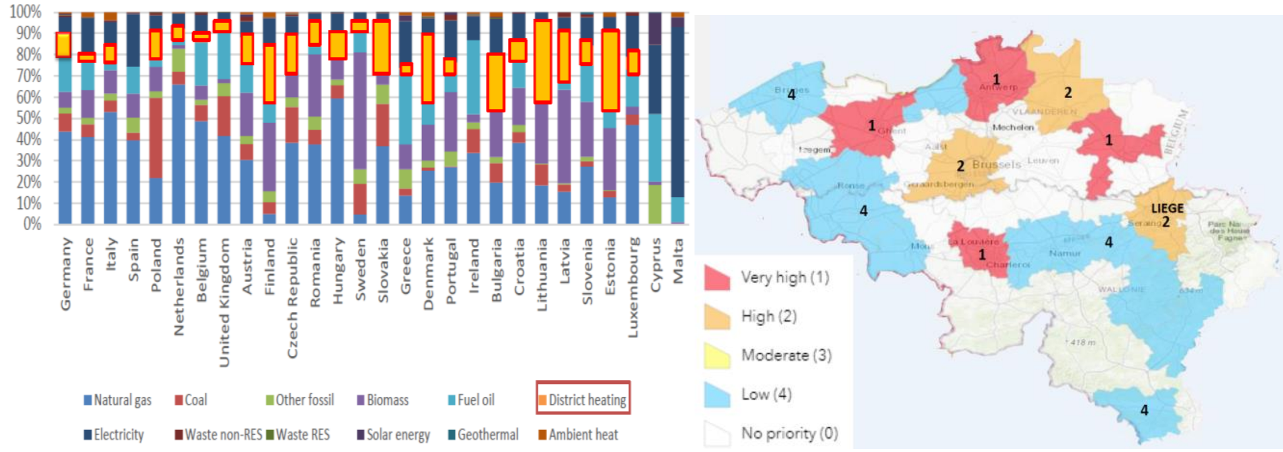
In the current context of energy transition, district heating systems are considered as a convenient yet efficient solution to reduce both primary energy consumption and greenhouse gases emissions. The use of locally available alternative heat sources, as for example the heat rejected by waste incinerators, constitutes an opportunity to valorize low-grade heat. Despite a higher initial investment cost, waste incinerators present the advantage to have a zero fuel cost that balances this initial capital expense. In the present contribution, a reference case study based on the *IEA EBC Annex 60* framework is used as a first attempt to explore dynamic effects related to the distribution of heat through district heating networks. It consists of a small set of reference dwellings with different heating profiles depending on the type of buildings and their level of insulation. The costs for the different operating scenarios and the consequent advantages of a combined heat and power waste incinerator as a heat source are determined. This paper illustrates the use of a plug flow dynamic model intended to predict the heat transport delay, the heat losses and the pumping work due to long piping instead of the classical steady-state approach usually used for district heating networks profitability assessment. A comparative assessment of both the unit cost of heat and CO_2 emissions savings is performed for two different heating technologies, namely a combined heat and power waste incinerator combined to backup boilers and a natural gas boiler.

Keywords:

Combined Heat & Power (CHP), District Heating Network (DHN), Dynamic modelling, Economic analysis, Waste incineration.

1. Introduction

District heating networks (DHN) seem to be a promising solution to meet the objectives fixed by the European Union in terms of CO_2 emissions reduction and primary energy savings. A reduction of the primary energy consumption and the integration of low-grade heat sources are some of the advantages of this technology [1]. As illustrated in Fig. 1(a), DHN (represented by highlighted boxes) are already well-developed in Nordic countries [2]. In Central Europe, this technology is less common but could be a promising alternative for the heating and cooling in the building sector. In Belgium, the heating and cooling demand includes half of the final energy demand of the country (around 165 TWh). Concerning excess heat sources, they are estimated above 68 MWh [3] which is equivalent to more than 40% of the total heating demand. Areas with high excess heat activities are interesting sectors to investigate in order to exploit the capacity of district networks to aggregate heat loads and waste heat rejection. A map of excess heat production in Belgium, represented in Fig. 1(b), can illustrate that there are some regions with a high potential for DHN [4]. In the frame of the present research project, particular attention is given to the city of Liège where a project of a DHN combined to a waste incinerator is being implemented.



(a) *(b)*

Fig. 1. Interesting data about DHN: (a) Repartition of EU heat sources [2], (b) Excess heat activities in Belgium [4].

Among all the legal, political and economic constraints related to the development of DHN projects, the significant initial investment cost, which includes the cogeneration plant, the piping and the substations, is certainly one of the most penalizing one [5]. An assessment of the heating costs for different scenarios is thus necessary to illustrate the possible savings in terms of energy consumption and costs. The supply and return temperatures in the network as well as the type of building heating technology influence the total system cost such that an optimization is necessary to minimize the final cost of heat. As already mentioned, one attractive solution is the use of a waste heat incinerator as a heat source. Economically, this solution makes sense as the zero fuel cost combined with the prospective of granted green certificates and/or other subsidies enables to leverage the initial investment costs [6]. The test case for DHN application provided by *Annex 60* [7] enables the assessment of the total costs related to these scenarios. Of course, the study relies on a virtual test case for which no measurement is available. However, all of the presented models have been tested and validated in previous works of the Thermodynamics laboratory of the University of Liège [8,9] and the presented results can be used for comparison purposes by other research teams as the test case data are publicly available.

2. The System Model

A cost appraisal of the whole system requires the calculation of the heat losses and the electrical pumping consumption along the network. A dynamic model of the DHN is used to compute these important values for 2 different heating scenarios prescribing supply and return temperatures of the water in the district heating network:

1. Scenario 90-60: supply/return temperatures are respectively prescribed to 90°C and 60°C.
2. Scenario 70-50: supply/return temperatures are respectively prescribed to 70°C and 50°C.

A dynamic model enables to assess mass flow rates distribution among all of the substations while taking into account inertia effects. Consequently, transportation delays of the heat waves from the heat source to the substations are estimated according to the pipes length. These phenomena can be easily handled through the use of dedicated dynamic simulation softwares. In the case of the present study, the software *Dymola* has been used [10]. As shown in Fig. 2, the theoretical case study used in this paper is representative of a neighbourhood made of 24 dwellings of different types with 2 specific levels of insulation (see [7] for details). From data about this case study, the thermal consumption related to the dwellings connected to the network is predicted through the resolution of a set of differential equations.

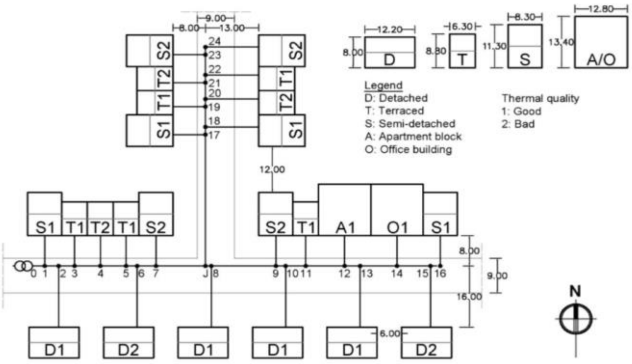


Fig. 2. Sketch of the Annex 60 Neighbourhood Case Study [7].

2.1. Dwellings Thermal Needs Model

The physical model of the dwellings heating requirement has been previously developed by the *Thermodynamics Laboratory* at the University of Liège [8]. For the modelling, dwellings are divided in different zones related to constant volumes of air supposed to be at a uniform temperature. As illustrated in Fig. 3, for example, detached (D) houses are divided in 5 different zones corresponding to specific parts of the house. The first one is related to the kitchen and the living room and the second one to the study. The third one represents the hall and the storage. The two last zones correspond respectively to the three bedrooms and the bathroom. These zones are connected together through mass and energy conservation equations taking into account heat and mass exchanges between zones and with the outside to determine energy requirements for each dwelling.

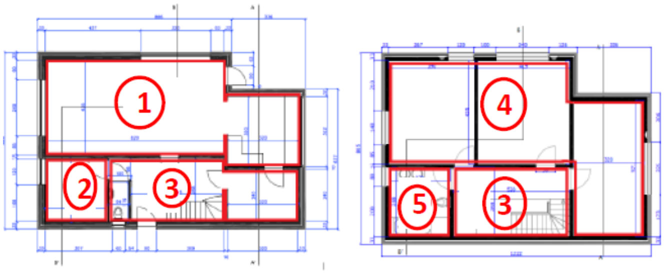


Fig. 3. Division of the detached (D) dwellings into zones: first (left) and second (right) floors [8].

It is assumed that there is no shading in the dwellings and weather data are based on a reference year in Uccle in Belgium. Heat transfers through walls and windows are computed using a network of thermal resistances *R [K/W]* combined with lumped capacitances *C [J/K]*. The thermal resistance corresponds to the resistance to conduction heat transfer through the walls and the lumped capacitance is intended to represent the thermal inertia of the wall material. For windows, inertia effects are neglected which is represented by a strictly resistive branch for the heat transfer model. The resulting model is made of the following set of differential equations [8]:

$$\begin{cases} \dot{q}_{in} = \dfrac{T_{wall} - T_{in}}{R_{in}} & (1) \\ \dot{q}_{out} = \dfrac{T_{out} - T_{wall}}{R_{out}} & (2) \\ \dot{q}_{out} - \dot{q}_{in} = C_{wall}.\dfrac{dT_{wall}}{dt} & (3) \end{cases}$$

In the above equations, T_{out} and T_{in} represent respectively the outdoor and indoor temperatures [°C] and T_{wall} corresponds to the mean temperature of the wall [°C]. In addition, solar irradiation is accounted for in the windows model through an additional heat rate added to the resistive model:

$$\dot{q}_{sol} = (1 - FWR).f_{sol}.(1 - f_{shad}).I_{sol} \qquad (4)$$

where FWR is the frame to window area ratio, f_{sol} and f_{shad} are respectively the solar and shading factors and I_{sol} is the solar irradiation $[W/m^2]$. These factors are determined by assuming the same type of double pane windows for all the dwellings [7].

Conservation equations are applied to connect the different zones together taking into account lighting, electrical appliances and building occupancy to build the complete model of a dwelling [8]:

$$\begin{cases} \frac{dm_{air}}{dt} = \dot{m}_{air,su} - \dot{m}_{air,ex} & (5) \\ \frac{dU}{dt} = \dot{Q}_{in} - \dot{Q}_{out} & (6) \\ \dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{windows} + \dot{Q}_{walls} + \dot{Q}_{inf} + \dot{Q}_{int} + \dot{Q}_{vent} + \dot{Q}_{TU} & (7) \end{cases}$$

with $\dot{Q}_{windows}$ corresponding to the heat flow through windows, $\dot{Q}_{walls}$ to the heat flow through walls, $\dot{Q}_{inf}$ to the heat rate due to air infiltrations, $\dot{Q}_{int}$ to the heat rate due to internal gains (lighting, appliances and occupancy), $\dot{Q}_{vent}$ to the heat rate due to the ventilation in the dwellings and $\dot{Q}_{TU}$ represents the heat input from terminal units for heating or cooling. $\dot{m}_{air,su}$ and $\dot{m}_{air,ex}$ are respectively the injected and extracted mass flow rates in each zone. U corresponds to the internal energy of the volume of air in each zone.

Based on this set of equations, a thermodynamic model of the whole dwelling is implemented by considering heat flows between adjacent walls and with the floor and the ceiling. A typical heating consumption is computed by resolving the dynamic model and by using weather data from Uccle as boundary conditions. The obtained results are illustrated in Fig. 4.

The total annual heating consumption in the network, without taking into account heat losses in the pipes, is around 574 MWh. These results exhibit the heat distribution across the different types of dwellings. It can readily be observed that well-insulated dwellings (type 1), with a level of insulation based on the directive 2010/31/EU of the European parliament, consume up to ten times less energy than the poorly insulated ones (type 2) with an average level of insulation corresponding to buildings insulation from 1946 to 1970 in Belgium. Obviously, a reduction of primary energy consumption related to the latter dwellings can be achieved by a deep retrofit towards low energy buildings [11]. However, such a retrofit is not always possible in real-life applications as this requires long-term inhabitants relocations and difficult permitting procedures. Inversely, the implementation of a district heating network is another way to reduce primary energy consumption through the use of highly efficient centralized heat production without the recourse to deep renovation processes. The resulting reduction of fuel consumption would be profitable from an economic and environmental point of view with a decrease of both cost of heating and CO_2 emissions. Moreover, it can be observed that even for the same level of insulation, heating demands are variable from one dwelling type to another. A dynamic simulation model is able to catch the high variability of the heat loads in order to assess the global performance of the system and the related costs.

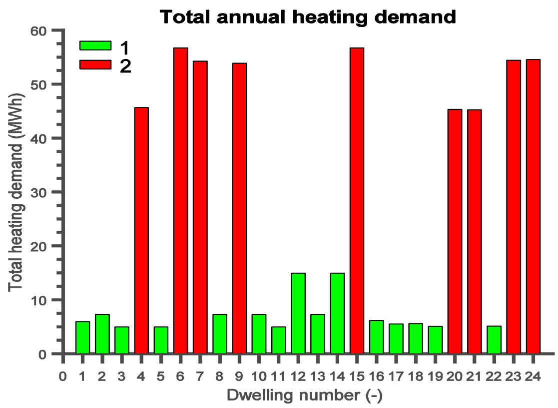


Fig. 4. Heating consumption over a reference year of the dwellings in the DHN.

In the case of the considered reference year, substations can be modelled by imposing the heating load profile on an hourly basis from off-line simulations. Figure 5 exhibits the heat consumption on an hourly basis over a reference year as a function of the outdoor temperature. The blue circles represent the consumption calculated by the dynamic model taking into account the thermal inertia while the red lines represent the steady-state consumption. For all the dwelling types, the dynamic solution exhibits a large scattering around the steady-state solution: for the same outdoor temperature, the predicted dynamic heat load can be twice or three times larger than the steady-state solution which claims for the use of dynamic models for the design of district heating networks. A simple interpolated heating curve using only the outdoor temperature as input is not representative of the dynamic effects occurring in the dwellings. An accurate estimation of the heating demand depends upon the previous states of the system and requires a dynamic or state-space modelling [12,13].

As already illustrated previously in Fig. 4, it can also be observed that hourly heating demands are logically higher for poorly insulated (type 2) dwellings than for well-insulated dwellings (type 1). Even though heating demand profiles follow a similar trend as a function of the type of dwellings, it can be seen that the energy consumption is dependent on the type of dwellings. For houses (categories D, T and S), an hourly typical energy consumption until around 5 kWh is observed. Energy consumption profiles seem to be similar for the different types of houses. However, for apartment blocks (A) and office buildings (O), heating demands are much higher due to larger floor areas to heat. The district heating technology has thus to be able to provide these different heat load profiles all over the year and to present a large flexibility to ensure various heating load requirements. In the following, an analysis of the results based on known simulation data from a reference year in Uccle is achieved.

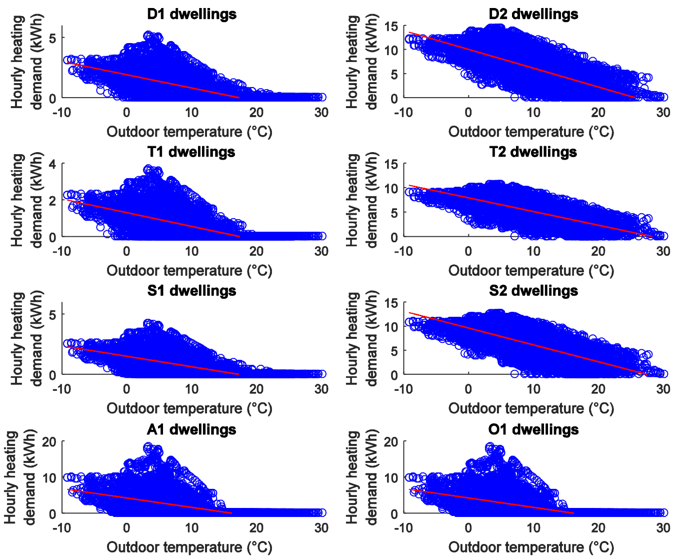


Fig. 5. Dwellings heating load profiles as a function of the outdoor temperature.

2.2. Piping Model

The piping model is a key part of the whole system model as it represents the link between the several consumption points and the heat production unit. Generally speaking, numerical methods used to model thermo-hydraulic flows in pipes are Finite Volume Methods [14]. As shown in Fig. 6, they consist in dividing the pipe in a discrete number of cells such that thermodynamic properties are computed in each cell applying conservation equations, namely the mass, momentum and energy balances. In order to keep the computational time in acceptable bounds, the cell size as well as the time step must be kept sufficiently large which leads, in turn, to numerical diffusivity. These aspects are detailed in [15] where the interested reader is referred to for more information.

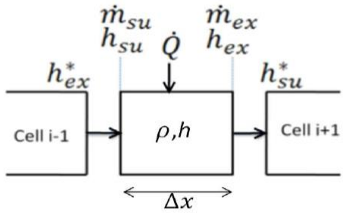


Fig. 6. Finite Volume Method as described in [15].

The so-called, Plug Flow method, is an alternative approach where thermodynamic properties are calculated only at both ends of the pipe. A delay function determines the residence time of a certain quantity of fluid within the pipe [15] in order to estimate the dynamic inertia effects. This method can be characterized as a Lagrangian approach as the motion of a fluid particle is followed as a function of time and initial conditions. The resulting model is an analytic expression of the pipe outlet temperature from conservation equations.

2.2.1. Time Delay

The time delay is computed from the one-dimensional wave equation enabling to compute properties of each fluid segment in spatial and time coordinates [16]:

$$\frac{\partial z(y,t)}{\partial t} + v(t)\frac{\partial z(y,t)}{\partial y} = 0 \qquad (8)$$

with $z(y,t)$ representing the transported quantity as a function of the normalized spatial coordinate y and $v(t)$ the normalized velocity of the fluid in the pipes. A more detailed explanation of the time delay model can be found in [16].

2.2.2. Heat losses calculation

The aforementioned plug flow method implemented in the *IBPSA* library [17] in *Dymola* is based on a combination of the energy and continuity equation. Neglecting axial diffusion and dynamic effects due to pressure losses and pipe frictions [16], the conservation equation can be written as followed:

$$\frac{\partial(\rho c_V A T)}{\partial t} + \frac{\partial(\rho c_V A v T)}{\partial x} = -\dot{q}_{losses} \qquad with\ \dot{q}_{losses} = \frac{T(t) - T_{sur}}{R} \qquad (9)$$

where A corresponds to the total circumferential area of the pipe, v is the velocity of the fluid in the pipe and $\dot{q}_{losses}$ represents heat losses along the pipe in W/m assuming a constant thermal resistance R between the pipe and its surroundings. Considering a constant surroundings temperature T_{sur} over the simulation time step and setting a constant heat capacity per unit length $C_V = \rho c_V A$, (9) can be integrated spatially on a non-zero infinitesimal step δx:

$$C_V \frac{dT(t)}{dt}\delta x = -\frac{T(t) - T_{sur}}{R}\delta x \qquad (10)$$

Integrating this ordinary differential equation on the time delay Δt computed from (8), the analytical expression of the pipe outlet temperature is:

$$T_{out} = T_{sur} + (T_{in} - T_{sur}).\,\mathrm{e}^{-\frac{\Delta t}{RC_V}} \qquad (11)$$

From (11), it can be seen that the outlet temperature is only dependent on the inlet temperature, the surroundings temperature and the time delay. Thermodynamic properties at intermediate positions inside the pipe are thus not necessary. Thermal inertia of the pipe is included in the model by an addition of thermal capacities to this plug flow model.

3. Economic assessment

The 2 scenarios mentioned in Section 2 are now used to determine the heat needs of the whole system through dynamic simulations. It is supposed that a prescribed heat source sets the inlet temperature of heat transport fluid (i.e. incompressible water) as a function of the heating set point imposed as input. This ideal heat source is supposed to be able to provide the required mass flow rate without any limitation. The total mass flow rate supplied to the network is thus computed as a function of the total heat demand and the prescribed temperature difference at the substations. A sketch of the corresponding model is supplied in Fig. 7 using components defined previously in Section 2.1 and 2.2 for dwellings and pipes. For the substations, the temperature difference at the primary side is imposed from the considered scenario and the heating load at the secondary side is based on the dynamic simulations for the dwellings from Section 2.2.

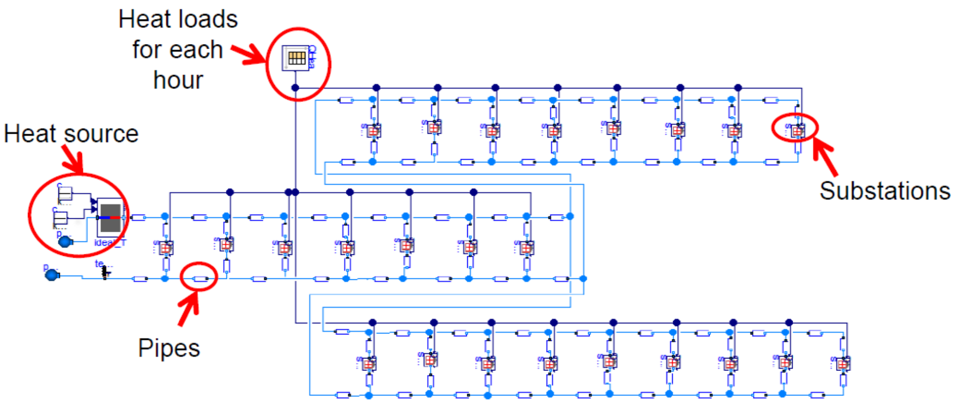


Fig. 7. Sketch of the whole DHN model for the Annex 60 Neighborhood Case Study.

The mass flow rate in each branch is obtained by applying mass conservation at each node of the network combined with an energy balance in each substation:

$$\begin{cases} \dot{m}_{in,node} - \dot{m}_{sub} = \dot{m}_{out,node} & (12) \\ \dot{m}_{sub} = \dfrac{\dot{Q}_{heat,sub}}{c_{p,w}.\Delta T_{sub}} & (13) \end{cases}$$

where $\dot{m}_{in,node}$ and $\dot{m}_{out,node}$ are the incoming and outcoming flows at each substation and $\dot{m}_{sub}$ is the mass flow rate feeding the substation for a prescribed temperature difference ΔT_{sub}.

If the pumps feeding the network are supposed to have an average efficiency η of 75% [18], a simple expression for the assessment of the total electrical pumping consumption in the network for a volumetric flow rate $\dot{V}$ with a pressure difference ΔP is given by (14):

$$\dot{W}_{pp,el} = \frac{\dot{V}.\Delta P}{\eta} \qquad (14)$$

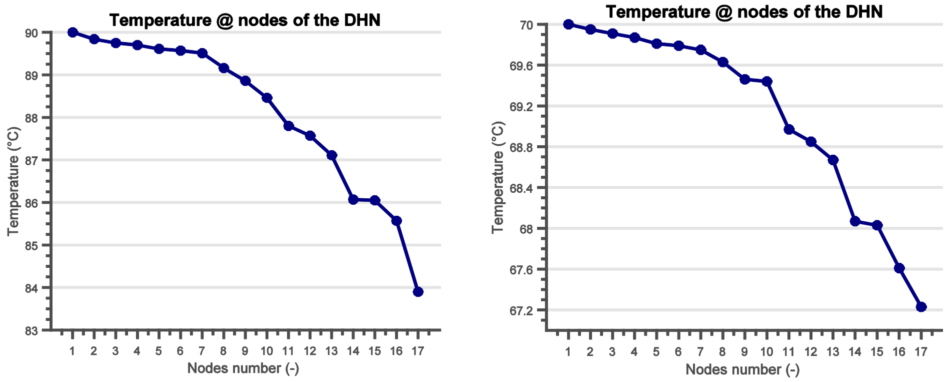
The problem, consisting of 22 358 unknowns, is solved using a DASSL integration algorithm and runs on a 2.8 GHz Intel Xeon processor. Results obtained from the dynamic simulations of the model are summarized in Table 1 for the 2 considered scenarios. It can be observed that there is a compromise to find between the minimization of the heat losses over the network and the total electrical consumption of the pumps. Indeed, using a smaller inlet temperature in the network with a smaller temperature difference at the substations reduces the total heat losses but increases the total pumping consumption as larger mass flow rates must be supplied at every substation.

Table 1. Mass flow rates, heat losses and pumping consumptions for the 3 scenarios

Scenario	Average mass flow rate, kg/s	Heat losses, MWh/year	Heat losses/Total heat production, %	Pumping consumption, kWh/year	Calculation time, h
90-60	0.525	57.3	9.07	483.7	8h30
70-50	0.783	44.3	7.16	1 028.1	9h45

Heat losses generate a temperature drop along the network such that substations at the end of the line are fed with a smaller inlet temperature. Figure 8 shows this evolution for both studied scenarios. It can be noted that the temperature profile is more or less constant for both scenarios.

This temperature profile is related to the length of the pipes. However, the temperature drop increases with higher inlet temperatures because of higher heat transfer through the pipe insulation towards the surrounding. An assessment of the total cost of heating including heat losses and electrical consumption must be stated.



(a) (b)

Fig. 8. Evolution of the average temperatures at the nodes of the network for the 2 studied scenarios: (a) 90-60 (b) 70-50.

This cost of heating (COH) can be defined similarly to the levelized unit cost of electricity (LCOE) which includes fixed and variable costs related to the operating conditions of the heating plant. Costs related to the DHN have also to be taken into account by adding the pipes cost, the total electrical pumping and heat losses. Based on the methodology developed in [19], the COH is represented by the following equation:

$$COH\ [€/MWh] = \frac{1}{\varepsilon_{DHN}}.\left(\frac{C.\psi+U_{fix}}{P_i.\tau_e}+\frac{y_F}{\eta_{th}}+u_{var}-(y_{el}+\tau_{GC}.y_{GC}).\frac{\eta_{el}}{\eta_{th}}\right) \quad (15)$$

with C corresponding to the investment cost in € (including the plant and the DHN costs) and ψ the annuity factor representing the evolution of the initial investment cost during the lifetime in years N of the project as a function of the discounting rate d:

$$\psi = \frac{d}{1-(1+d)^{-N}} \quad (16)$$

U_{fix} represents the fixed costs in € related to operation and maintenance costs and u_{var} corresponds to the variable costs in €/MWh, including especially pumping costs. ε_{DHN} is the ratio between the total heat demand in the network and the total heat production of the plant taking into account heat losses over the network. P_i is the installed power in MW of the plant that has to be determined in order to minimize the total COH. τ_e[h] is the equivalent utilization time of the plant, i.e. the ratio between the total energy produced by the plant during the year and the installed power of the plant. For a combined heat and power plant, thermal and electrical efficiencies η_{th} and η_{el} are defined respectively as the ratio between the electrical/thermal power production and the primary power used. y_F and y_{el} are respectively the fuel and electricity cost in € per MWh. An additional factor in the COH assessment takes into account whether or not green certificates are granted at a rate τ_{GC} for each MWh of electricity produced by the combined heat and power plant at a price y_{GC} [€/MWh]. From (15), two calculations of the COH for each type of heating plant is considered:

1. Combination of a combined heat and power waste incinerator for base load production and backup boilers for peak heating production.
2. Use of a natural gas boiler.

The sizing of the plants and the assessment of the costs is based on the heat load profile of the network (illustrated in Fig. 9). The sizing of the natural gas boiler is based on a peak heating power of 203 kW. Concerning the combined heat and power plant waste incinerator, the installed power has to be determined to minimize the total COH including the backup boilers costs.

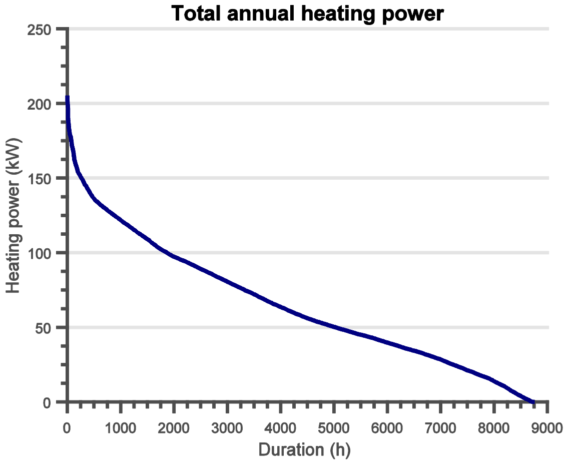


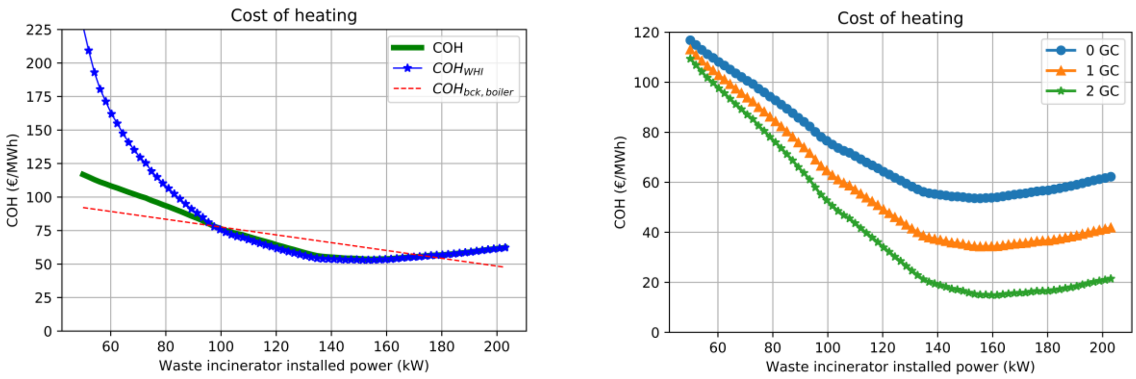
Fig. 9. Total heating power demand over the year for the Annex 60 Neighborhood Case Study.

Considering a lifetime of 20 years for both installations, a discount rate of 5% per year, a value of 65 € for each green certificate obtained and based on data from Table 2 [20-21], results computed for the first scenario are plotted in Fig. 10.

Table 2. Cost data for the 2 different studied plant technologies [20-21]

Technology	C, *€/kW*	U_{fix}, *€/kW/y*	u_{var}, *€/MWh*	Fuel price y_F, *€/MWh*	Electricity price y_{el}, *€/MWh*	Thermal efficiency η_{th}, %	Electrical efficiency η_{el}, %	CO_2 emissions, kg/MWh
Waste incinerator	1200	54	5.6	0	110	70	20	149
Natural gas boiler	600	200	4.5	35	110	45	40	198

Figure 10 (a) shows that the cost of heating related to the incinerator reaches a minimum for an installed power around 152 kW. Regarding costs related to the backup boilers, it is observed that they decrease monotonously with an increased installed power for the waste heat incinerator. For the first scenario (90-60), the minimization of the total COH is obtained for an installed power of the waste incinerator around 155 kW.



(a) *(b)*

Fig. 10. (a) Cost of heating (COH) as a function of the installed power of the cogeneration waste heat incinerator without green certificates for the 90-60 scenario. (b) Influence of the number of green certificates on the COH for the 90-60 scenario.

A summary of the COH computed for the different scenarios is presented in Table 3. It is important to note that the assessment of the COH for the combined heat and power plant waste incinerator is calculated in the most pessimistic case where no green certificates are granted. A parametric analysis computing the COH as a function of the allocated number of green certificates is presented in Fig. 10 (b).

Table 3. Cost Of Heating (COH) for the different considered configurations (without green certificates)

COH (€/MWh)	90-60	70-50
Waste incinerator	53.6	**52.5**
Natural gas boiler	99.7	97.8

It can be seen from *Table 3* that the cost of heating is lower with a combined heat and power plant waste incinerator combined with backup boilers than with a natural gas boiler only. This result is explained by the fact that wastes are freely available thus cancelling the fuel cost and compensating higher fixed initial investment costs. As far as operating strategies are concerned, lower operating temperatures seem to be more interesting from an economic point of view as they decrease the heat losses and thus reduce the operating costs.

Obviously, Fig. 10(b) illustrates that the cost of heat can be further decreased with green certificates granted. The two main factors influencing the allocated number of green certificates are the CO_2 emission level and the year of construction of the plant.

Concerning CO_2 emissions reduction, the use of a combined heat and power plant waste incinerator with backup boilers instead of a simple gas boiler appears to be an efficient solution. Throughout a year, CO_2 savings can be quantified by the difference between CO_2 emissions from a natural gas boiler and a waste incinerator combined with backup boilers. A total saving of 26.5 tons of CO_2 per year is achieved for the optimal 70-50 scenario offering thus an environmental advantage in addition to the lower cost of heating by using a waste incineration technology as heat source in a district heating network.

4. Conclusions

In this contribution, a dynamic model of a virtual district heating network with 24 dwellings represented by 24 substations and 96 pipes has been presented. After a problem statement and a detailed presentation of the different components used in the model, an assessment of the heat demand, pipe heat losses and pump electrical consumption has been achieved. From these consumption data, an economic analysis has been performed taking into account the total cost of the DHN combined to a power plant. A dynamic model using simple and robust components which could be readily reused for more complex systems has been implemented with relatively fast simulation speeds of a few hours. In the case of the current research project, these components are validated on a theoretical case study and can therefore be used as a reference for the modelling of more complex networks. Moreover, the economic analysis has shown that the use of a waste incinerator as heat source in a district heating network is very interesting because of the lower cost of heat than with a natural gas boiler due to the zero waste cost and the lower global CO_2 emissions. Concerning operating conditions, lower supply temperatures are related to less heat losses enabling to reduce the total heat production. Even though the electrical pumping consumption increases due to higher mass flow rates with smaller supply temperatures, the more consequent decrease of heat losses over the network encourage DHN managers to operate at low temperatures.

For the future, it will be interesting to assess performance of the heat exchangers at the substations as a function of the supply temperature which decreases along the network, being minimal at the end of line. An adaptation to other real networks will also be lead and it will be tried to automate the generation of a dynamic model of DHN based on geographical data systems. After this automation, an optimization loop will be used to determine optimal operating strategies and network configurations for defined neighbourhoods.

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Nomenclature

Physical quantities

A circumferential area of the pipes, m^2

c specific heat, J/(kg K)

C lumped thermal capacitance, J/K

f_{sol} solar factor, -

f_{shad} shading factor, -

FWR Frame to Window Ratio, -

h enthalpy, J/kg

I solar irradiation, W/m^2

$\dot{m}$ mass flow rate, kg/s

$\dot{q}$ heat flow per square meter, W/m^2

$\dot{Q}$ heat flow, W

R thermal resistance, K/W

T temperature, K or °C

U internal energy, J

v fluid velocity, m/s

$\dot{V}$ volumetric flow rate, m^3/s

ΔT temperature difference at the primary side of the substations, K or °C

ΔP pressure difference, Pa

Greek symbols

η efficiency, -

ρ fluid density, kg/m^3

Subscripts and superscripts

a Air

bck Back-up

ex Exhaust

in Indoor

inf Infiltration

int Internal gains

out Outdoor

sha Shading

sol Solar

su Supply

sub Substation

sur Surroundings

TU Terminal Units

vent Ventilation

w Water

Other symbols

COH Cost Of Heating

DHN District Heating Network

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