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Temperature level optimization for low-grade thermal networks using the exergy method

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Abstract. Low-temperature thermal networks open the field for additional renewable and recovered energy sources to be used. The exploitation of low exergy level resources requires decentralized heat pumps having a significant impact on the network's overall electricity consumption. Thus, a compromise must be found in order to minimize thermal and electrical consumption while integrating a maximum of renewable energy sources. This optimum is governed by the temperature level of the network. This paper aims at determining the optimal network temperature using the exergy criterion. The exergy method is detailed and applied to the multi-source network blueCAD (Fribourg) fed by geothermal energy, and FriCAD, a high temperature district heating network. The optimum temperature decreases as the share of geothermal energy in the production increases. For blueCAD, it ranges from 40 to 55 °C.

1. Introduction

About 85% of energy for heating and cooling typically derives from fossil fuels (natural gas, coal, oil products...). IRENA estimates that the share of renewable energy in this sector could reach 34% by 2030 [1]. Thermal networks are an opportunity to mutualize resources to provide heating, hot water and cooling services, especially in densely populated areas [2]. By lowering their temperature levels, they can simultaneously provide these services while integrating renewable energy resources with low exergy content [3]. Depending on the temperature, substation configuration needs to be adapted [4]. Therefore, several network models can be considered [2]: medium-temperature networks (70/60 °C) consisting only of heat exchanger (HE) substations for heating and hot water supply; intermediate temperature levels networks (55/35 °C) that can integrate heat exchangers for heating and heat pump units for domestic hot water production (DHW); anergy networks (8/12 °C) using decentralized heat pump units (HPs) for heating and domestic hot water production coupled with cooling heat exchangers in summer. The same applies to the production plant, whose configuration depends on the sources and the network temperature levels. Source-related criteria are often constraints that are difficult to manage. To match the demand with the available resources of a given district, determining the optimal temperature level of the distribution network is necessary to minimize global consumption and improve the network's global efficiency. Indeed, down to a certain level of temperature, the thermal energy consumption decreases significantly, although the use of centralized/decentralized heat pumps (HPs) is necessary to raise the temperature enough for supply to buildings [5]. The study [6] shows that it implies an important electrical consumption, especially in winter, because of high temperature differentials that the heat pumps must achieve. Moreover, by lowering the temperature, the power consumption of the circulation



pumps increases with flow rates and the pressure drops [7-8]. An optimization problem arises between the total electrical and thermal consumption of the network [9]. The concept of multi-energy systems adopts a blackbox approach with disjointed thermal and electrical energy balances [10]. These studies conclude on the increase or decrease of the thermal energy consumption on one side, and of the electrical consumption on the other side, compared to a reference scenario. Nevertheless, the limitation of the energy criterion is that it does not allow comparison on a common basis of the electrical and thermal consumptions [11]. Exergy analysis allows comparison of all forms of energy (electricity, heat) entering and leaving a thermodynamic system, to locate explicitly the internal losses of the system and to establish its efficiency.

This study aims to determine the optimal network temperature on an exergy basis. The exergy criterion is used to compare electrical and thermal consumption on a common basis, in order to determine an optimal network temperature. The method used to find the optimum temperature while minimizing the global exergy consumption is detailed and applied to the application case of the blueCAD network, an advanced and innovative thermal network concept designed for the blueFACTORY neighborhood (Fribourg, Switzerland).

2. Problem description

blueFACTORY is a growing neighborhood in the heart of the city of Fribourg (Switzerland). Its objective is to become a "zero emission" district by 2040. In 2040, 17 buildings should be on-site. As part of the blueCAD project [2] led by the Thermal & Energy Laboratory, a new concept of advanced low-temperature thermal network is being proposed to provide heating (5,6 GWh/an), cooling (0,5 GWh/an) and domestic hot water (2 GWh/an) services (Figure 1). The estimated electrical requirement of the site is 2.7 GWh/year. The system would operate with a temperature level adjusted according to the seasons thanks to a control unit enabling smart management and integration of renewable energy sources.

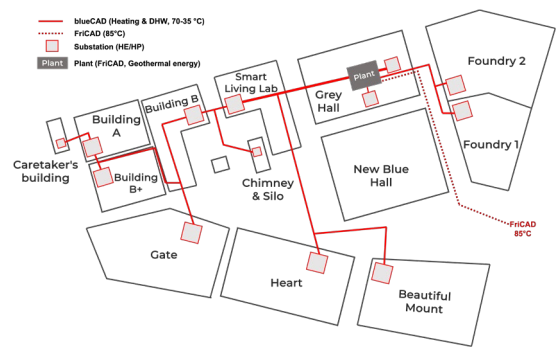


Figure 1. blueCAD's network

The energy resources available are geothermal energy (10°C) and FriCAD, the high temperature network of Fribourg (85 °C). In practice, blueCAD can operate between 35 and 55 °C. The objective of this study is to determine the network temperature for which the total exergy consumption is minimal. The thermal network consists of several entities: a production plant fed by energy sources (geothermal, FriCAD), a distribution network and substations to provide heating and hot water services to customers. Each of these entities has to be modeled. A "superstructure" gathers all the systems/resources that can be used for a given entity. Depending on the considered temperature levels, different thermodynamic systems are used (HE, HP): the configuration of an entity is then fixed. Figures 2a and 2b illustrate the superstructures of blueCAD's plant and substations. The "network temperature level" refers to the plant outlet flow temperature supplying blueCAD's distribution network.

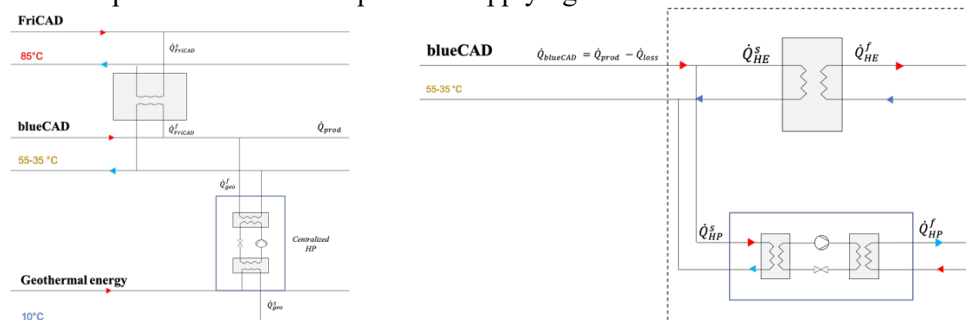


Figure 2. Thermal network superstructures: (a) Plant superstructure, (b) Substation superstructure

2.1. Plant superstructure

The production plant is fed by sources to provide the thermal power production of the network \dot{Q}_{prod} . This power includes thermal losses \dot{Q}_{loss} as well as the energy to satisfy the demand $\dot{Q}_{blueCAD}$ giving the efficiency of the substation energy system. The configuration of the plant changes according to the source and distribution network temperature levels, as shown in Figure 2a. In the scope of the study, two energy sources are considered: geothermal energy with a constant temperature level of 10°C and the high temperature network FriCAD whose temperature level is constant at 85°C. The superstructure of the plant consists of a heat exchanger, ensuring the interconnection between FriCAD and blueCAD and a centralized heat pump for the geothermal energy. Moreover, to compare the results, two reference networks are set as the case where blueCAD is: an anergy network of 10 °C, the plant is not operating and only decentralized heat pumps are used in the substation. Therefore, it represents the maximal power consumption; a high temperature network of 70 °C where only FriCAD supplies blueCAD and heat exchangers, this is the maximum thermal consumption reference.

2.2. Substation superstructure

The substations are fed by the distribution network (primary network) in order to provide the heating and hot water services to the customers (secondary network). Cooling is not considered. In this study, the system boundary is limited to the conversion units; the secondary network of the building is not modeled. Figure 2b defines the system boundary (dashed lines). The temperature differential in the substation is set for each customer and adapted according to the temperature level of the network. The setpoint temperature for heating buildings is 40 °C and for the domestic hot water setpoint temperature it is 55°C.. When the inlet temperature at the substation is lower than the latter, a decentralized heat pump is connected to raise the temperature. Thus, the substation superstructure is composed of heat exchangers and decentralized heat pumps for both heating and DHW services.

3. The Exergy Method

The exergy method applied to thermal networks allows determination of the optimal temperature, thereby minimizing the total exergy consumption of the network. It also allows quantification of the global exergy losses according to the temperature level of the network.

First, when all configurations are known, the network scenario is modeled using the ADVENS simulation platform [2]. The latter establishes the flow and temperature distribution on the distribution network according to the network discretization quantum methodology [12]. Then, the total thermal exergy consumption $\dot{E}_{q_{in}}$ and electricity consumption \dot{E}_{in} are compared as a function of the temperature level of the network. The global exergy consumption of the system \dot{E}_{tot} is defined as:

$$\dot{E}_{tot} = \dot{E}_{q_{in}} + \dot{E}_{in} \quad (1) \quad \text{with } \dot{E}_{q_{in}} = \dot{E}_{q_{geo}} + \dot{E}_{q_{FriCAD}} \quad \text{and} \quad \dot{E}_{in} = \dot{E}_p + \dot{E}_{HP,c} + \dot{E}_{HP,d}$$

\dot{E}_p , $\dot{E}_{HP,c}$, $\dot{E}_{HP,d}$ the electrical consumption of the circulation pumps, centralized/decentralized HPs and $\dot{E}_{q_{FriCAD}}$, $\dot{E}_{q_{geo}}$ the thermal exergy supplied by the sources.

3.1. Distribution network modelling

The distribution network is composed of supply-return pipes and circulation pumps. It is fed by the plant which provides the energy necessary to cover thermal losses and satisfy customer demand. Knowing its topology as well as the customer demand, the quantum network discretization methodology [12] is used to model the network. The circulation pumps must overcome total pressure drops ΔP_{tot} . As a first approach, their electrical consumption is expressed as:

$$\dot{E}_p = \frac{\dot{V} \Delta P_{tot}}{\eta_{pump}} \quad (2) \quad \text{with } \eta_{pump} = 40 \% \quad \text{and } \dot{V} \text{ the total volume flow rate (m}^3 \cdot \text{s}^{-1}\text{)}.$$

3.2. Thermal plant modelling.

The plant superstructure is shown in Figure 2a. The modeling of the network allows calculation of \dot{Q}_{prod} . Afterwards, it is necessary to quantify the different energies involved for the exergy balance of

the overall system. In our case, the production is delivered by the centralized heat pump \dot{Q}_{geo}^s and the network FriCAD \dot{Q}_{FriCAD}^s .

3.2.1. Geothermal percentage. The centralized heat pump (geothermal energy) and the centralized heat exchanger (FriCAD) can either operate simultaneously or not. A control strategy of the thermal plant is defined to determine the respective operating rate of these units. For this purpose, the “geothermal percentage” X_{geo} is defined. It is the amount of energy produced by the plant that comes from geothermal energy, meaning the amount of thermal energy supplied at the condenser of the centralized heat pump \dot{Q}_{geo}^f . Thus, when it is set to 100%, only the centralized heat pump operates:

$$X_{geo} = \frac{\dot{Q}_{geo}^f}{\dot{Q}_{prod}} \quad (3) \quad \text{with } \dot{Q}_{geo}^f = X_{geo} \dot{Q}_{prod}, \quad \dot{Q}_{prod} = \dot{Q}_{FriCAD}^f + \dot{Q}_{geo}^f, \quad \dot{Q}_{FriCAD}^f = (1 - X_{geo}) \dot{Q}_{prod}$$

3.2.2. Centralized HP (Geothermal energy). In order to determine the thermal power \dot{Q}_{geo}^s supplied by the geothermal source, the generic formula of heat pump exergy efficiency η from [4] is used.

$$\eta(T_h, T_c) = 1 - \frac{T_a}{T_h} \left[1 - \eta_{Ks} \cdot \Delta s / c_p \cdot \frac{\frac{T_h}{T_c} - 1}{\frac{T_h + \Delta T_h}{T_c - \Delta T_c} - 1} \right] \quad (4)$$

with ΔT_c and ΔT_h being the evaporator and condenser pinches, T_h the temperature of the heat sink, T_c the temperature of the heat source, η_{Ks} the isentropic compressor efficiency, Δs the entropy differential during the evaporation process and c_p the mass heat capacity considered constant as the average between the inlet and outlet of the compressor. The effective coefficient of performance (COP) of the heat pump is a function of the ideal COP and the exergy efficiency: $COP_{max} = \frac{T_h}{T_h - T_c}$, $COP_{real} = \eta(T_c, T_f) \cdot COP_{max}$

Therefore, the thermal exergy from the geothermal source is expressed as:

$$\dot{E}_{q_{geo}} = \left(1 - \frac{T_a}{T_{geo}} \right) \dot{Q}_{geo}^s \quad (5) \quad \text{with } \dot{Q}_{geo}^s = \left(1 - \frac{1}{COP_{real}} \right) \dot{Q}_{geo}^f$$

3.2.3. Centralized HE (FriCAD). Assuming a heat exchanger energy efficiency of $\eta_{HE} = 95\%$, the thermal exergy from FriCAD is defined as:

$$\dot{E}_{q_{FriCAD}} = \left(1 - \frac{T_a}{T_{FriCAD}} \right) \dot{Q}_{FriCAD}^s \quad (6) \quad \text{with } \dot{Q}_{FriCAD}^s = \frac{\dot{Q}_{FriCAD}^f}{\eta_{HE}}$$

3.3. Substation modelling

Figure 2b shows an example of a substation configuration. A distinction is made between the thermal production for heating and the thermal production for domestic hot water with decentralized units specific to each case (heat exchangers or heat pumps). When decentralized heat pumps are used for heating and/or DHW, the power consumption of the compressor is expressed as:

$$\dot{E}_{HP,d} = \frac{\dot{Q}_{HP,d}^f}{COP_{real}} \quad (7) \quad \text{with } \dot{Q}_{HP,d}^f \text{ the thermal power delivered to the customer.}$$

4. Results and discussion

The exergy method is applied to predict blueCAD’s optimal temperature level by 2040. The objective is to determine the optimal temperature level of the distribution network, and thus the configuration minimizing the total exergy consumption. Here, the temperature level of the distribution network varies between 10 °C and 70 °C, which are the reference points.

In order to determine the optimal temperature according to the energy sources available, the **thermal exergy consumption** $\dot{E}_{q_{in}}$ and power consumption \dot{E}_{in} are plotted as a function of the network temperature level. Regardless of the geothermal percentage, an exergy optimum of temperature exists. Figures 3a and 3b represent the evolution of the annual thermal exergy (red curve) and electricity (blue curve) consumption according to the temperature level of the network (and therefore according to its

configuration). For Figure 3a, the geothermal percentage is set to 30%, and 70% for Figure 3b. The sum of the annual thermal exergy and electricity consumption (green curve) highlights a temperature corresponding to the minimal exergy consumption. Indeed, given a certain temperature level, a significant increase in power consumption appears as the temperature gets higher. It is due to the temperature gap that the centralized heat pump must compensate for, between the source (10 °C) and the network (50-70 °C).

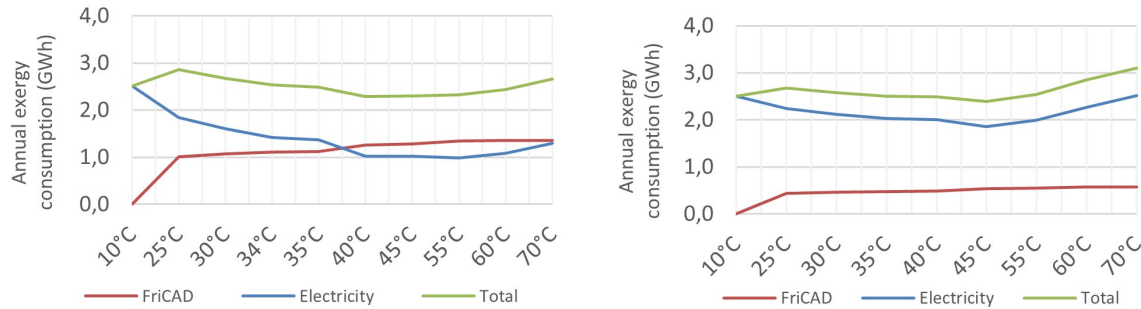


Figure 3. Application to blueCAD: Annual exergy consumption as a function of network temperature level for 30% (a) and 70% (b) of geothermal energy in production

Whether for low or high geothermal percentages, the shape of the total consumption curve is governed by electricity consumption. Indeed, the thermal exergy of FriCAD increases because of thermal losses in the network. This variation is relatively small compared to the consumption of centralized and/or decentralized heat pumps which have to overcome a more or less high temperature differential between hot and cold sources. For low temperatures (10-40 °C), only decentralized HPs are used in the substations. The power consumption decreases because the temperature differential which must be bridged is lower. This decrease is even more visible when the geothermal percentage is low because the centralized heat pump is less used. For high temperatures (50-70 °C), the total exergy consumption increases with the geothermal percentage because of the significant electrical consumption of the centralized HP, as shown in Figure 3b.

Finally, the optimal temperature depends on the geothermal percentage and thus on the available sources. Figure 4 shows the evolution of the total annual exergy consumption as a function of the temperature level, considering several geothermal percentages. The optimal temperature is in all cases between 35 °C and 70 °C. It decreases as the geothermal percentage increases. Thus, if the geothermal percentage is between 0 and 30%, the temperature optimum is between 55°C and 60°C. For a percentage higher than 50%, this temperature is between 40 and 45 °C. Moreover, total annual exergy consumption increases with the geothermal percentage. However, the supply sources of the FriCAD network are not considered in the scope of this study.

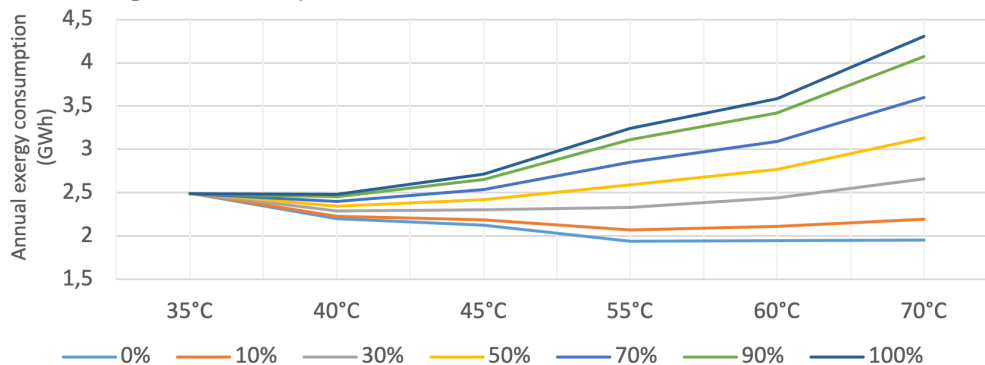


Figure 4 Annual exergy consumption as a function of temperature for different geothermal percentages

In the specific case of blueCAD, the share of geothermal energy in the production is 70%. With this geothermal percentage, the optimal temperature is around 40 °C. Figure 3b shows that the thermal exergy consumption is relatively low compared to the power consumption: the thermal exergy from FriCAD is 0.5 GWh/year against an average of 2 GWh/year for electricity.

5. Conclusion

The approach developed here allows the determination, on an exergy basis of the optimal temperature of a network according to the percentage of geothermal energy available on the site. This optimum tends to approach the temperature of the source having the largest contribution to the production. Thus, for low percentages of geothermal energy in the production, the temperature optimum minimizing the global exergy consumption is high in the case of blueCAD, because the second source is a high temperature network of 85 °C. When the share of geothermal energy increases, the temperature optimum decreases to be closer to the geothermal energy temperature level (fixed at 10°C in this study). Depending on the available sources, the same process can be implemented to correctly operate the network. This methodology for identifying the optimal temperature of a thermal network offers valuable information to network operators both in the operation and design phases. Indeed, minimizing the exergy consumption means minimizing the network operating costs. In the design phase, this methodology enables, in our case, the prediction of the quantity of geothermal probes to be deployed. In order to improve the model, further work will assess the distribution of the exergy losses generated by the different systems of the network for the optimization of its global performance.

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