Multi-criteria analysis of district heating system operation strategy

Dražen Balic^a, Danica Maljković^a, Dražen Lončar^b
^aEnergy Institute Hrvote Požar, Savska cesta 163, 10000 Zagreb, Croatia
^bFaculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Ivana Lučića 5, 10000 Zagreb, Croatia

ABSTRACT

The contemporary energy system is faced with new challenges on the energy market. Both the rising share of renewable-based electricity (characterised by intermittent production) and increasing energy efficiency in buildings induce a reconsideration of the traditional role of conventional power plants coupled with district heating systems along with its impact on the energy system. Moreover, the price of electricity determined by the merit-order system additionally decreases the load factor of such plants, making them less competitive or even inflicting financial loss in operation. Research presented in this paper focuses on a novel approach towards conventional combined heat and power (CHP) plants coupled with district heating systems. It involves an analysis of dynamical performances of the district heating system – capability of energy accumulation and thermal inertia – in order to assess its potential to become part of ancillary services. It is concluded that the district heating system, i.e. network of pipelines can be considered as dynamical thermal energy storage in which excess energy can be stored during operation of the CHP plant. A comprehensive analysis of dynamic behaviour of the district heating system has been performed by means of a mathematical model developed as a part of this research. The model is implemented on a theoretical case consisting of a simplified district heating system with three final users and the pipeline network of 9000 m in length. The simulation has shown that the storage capacity of the network depends on the thermal load in the network and in such circumstances specific thermal capacity of the network amounts to 10.1 Wh/(km). If the thermal load is decreased by 13% at the peak the accumulation capability is decreased by 40%. Moreover, the thermal capacity of the network increases up to 13.7 Wh/(km) as the pipeline length declines to 1000 m which is characteristic of densely populated areas. The capability of energy accumulation is explored for different parameters, such as: external temperature, distance of the network, supply water temperature etc. It is shown that distance of final users from CHP plant has certain impact on the operation strategy as well. Final users closer to the CHP plant determine operation strategy in the case of short-term disturbances in heat supply, while the farther ones in the case of long-term disturbances.

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1. Introduction

Deployment of district heating systems coupled with the Combined Heat and Power (CHP) plants, also known as cogeneration units, presents a more efficient way of primary energy use. In contrast to the more advantageous trigeneration systems, CHP plants are simpler and economically more acceptable, especially with respect to investment costs. Nowadays, cogeneration units are mostly based on conventional fossil fuels.

District heating systems have a long tradition in supplying heat to households in densely populated areas. This type of system is considered to be one of the most efficient ways of heating – it is of significant importance due to the endeavours aiming at lowering energy consumption by increasing energy efficiency. According to [1] the annual district heating market turnover in the EU 27 amounts to approximately 840 TWh, while in 2013, the total district heat delivered in the Republic of Croatia amounted to 2.3 TWh [2]. Apart from the fact that district heating has an important role in the present energy system, it is expected that district cooling will become largely deployed [1] as well. An extensive report upon both of these systems is given in [3] where different aspects (economic, environment, technical) are discussed.

In order to determine the performance of the district heating systems which can be further used for applying various optimization procedures, many authors give specific approaches. In [4], a novel mass flow control as well as network design is proposed. Moreover, the non-linear temperature program is adopted result-
tuning method for such controllers, while Menon et al. [12] consider optimal predictive control strategies in order to integrate various systems such as microgrids, cogenerations, heat pumps etc. Another view on the modelling of optimization strategies, i.e. control systems is given in [13] where the heating, cooling and electrical demands are being forecasted on a dynamic basis. An interesting approach regarding broadening of possibilities in operation strategy of the district heating system is given in [14] where residential buildings are used as a thermal storage. Namely, it is shown that by slightly varying the heat released to the district heating network and consequently the indoor temperature, buildings have enough thermal inertia to be used as the thermal storages. Wu et al. in [15] researched air source absorption heat pump coupled with low temperature district heating system. In [16], it is asserted that district heating systems coupled with cogenerations have a low load factor due to the fact that during the warm periods of the year heat demands are reduced. In this sense, deployment of the absorption heat pump is proposed. In addition, the reduction of CO₂ emissions is expected in comparison to electric driven chillers. Moreover, regarding CO₂ emissions, in [17] it is shown that district heating systems can significantly contribute to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria and has contributed to CO₂ emissions reduction.

Analysis of the reduction of the pumping and thermal loss costs in an indirect district heating system was carried out by Jie et al. in [9]. In [10] a thorough analysis of the impact of heat exchanger between the primary and secondary mass flow is given. Moreover, transient models for each district heating subsystem are developed, as well as the control system in a final user substation. Dobos and Abonyi in [11] deal with a non-linear model predictive controller in order to determine adequate control strategies, i.e. the tuning method for such controllers, while Menon et al. [12] consider optimal predictive control strategies in order to integrate various systems such as microgrids, cogenerations, heat pumps etc. Another view on the modelling of optimization strategies, i.e. control systems is given in [13] where the heating, cooling and electrical demands are being forecasted on a dynamic basis. An interesting approach regarding broadening of possibilities in operation strategy of the district heating system is given in [14] where residential buildings are used as a thermal storage. Namely, it is shown that by slightly varying the heat released to the district heating network and consequently the indoor temperature, buildings have enough thermal inertia to be used as the thermal storages. Wu et al. in [15] researched air source absorption heat pump coupled with low temperature district heating system. In [16], it is asserted that district heating systems coupled with cogenerations have a low load factor due to the fact that during the warm periods of the year heat demands are reduced. In this sense, deployment of the absorption heat pump is proposed. In addition, the reduction of CO₂ emissions is expected in comparison to electric driven chillers. Moreover, regarding CO₂ emissions, in [17] it is shown that district heating systems can significantly contribute to CO₂ emissions reduction. Torchio in [18] carried out an analysis and compared district heating CHP with distributed generation CHP on the basis of several criteria such as energy consumption, environmental impact and costs related issues. The district heating CHP system has met the best results by each criteria. Interesting research was conducted in [19] where authors have examined dynamical interaction between CHP and district heating systems which was a good starting point for the research presented in this paper. In [20], impact of excess heat production from Net Zero Energy Buildings in Denmark on the district heating system is investigated, with a focus on heat from solar thermal collectors. The results of this analysis show that excess heat from

### Nomenclature

- $M_{3,i}$: mass of the water inside the $i$-th supply pipe segment (kg)
- $m_{3,i}$: mass flow in $i$-th supply pipe (kg/s)
- $m_{R,i}$: mass flow in $i$-th return pipe (kg/s)
- $m_{FU,i}$: mass flow at $i$-th final user (kg/s)
- $m$: total mass flow (kg/s)
- $L_{3,i}$: length of the $i$-th supply pipe segment (m)
- $L_{R,i}$: length of the $i$-th return pipe segment (m)
- $Δp_{3,i}$: pressure drop along the $i$-th supply pipe segment (Pa)
- $Δp$: pressure increase on the circulation pump (Pa)
- $Δp_{max}$: maximal pressure increase on the circulation pump (Pa)
- $n$: number of revolution of the circulation pump (–)
- $n_{max}$: maximal number of revolution of the circulation pump (–)
- $ρ$: water density (kg/m³)
- $Q_{max}$: maximal volume flow on circulation pump (m³/s)
- $D_{3,i}$: Diameter of the $i$-th supply pipe segment (m)
- $K_i$: valve constant at $i$-th final user (–)
- $Y_i$: valve openingness (–)
- $c_w$: specific thermal capacity of the water (J/(kg K))
- $τ_p$: convective heat transfer coefficient from water to the inner side of the steel pipe (W/(m² K))
- $A_{3,i}$: area of the $i$-th supply pipe (m²)
- $Δt_{3,i}$: temperature of the water in the $i$-th supply pipe (°C)
- $Δt_{p,3,i}$: temperature of the $i$-th steel supply pipe (°C)
- $M_{3,i}$: mass of the $i$-th steel supply pipe (kg)
- $c_p$: specific thermal capacity of the steel (J/(kg K))
- $k_p$: heat transfer coefficient from the inner side of the steel supply pipe to the environment (W/(m² K))
- $v_E$: temperature of the environment (°C)
- $v_{FU,i}$: temperature of the water at the exit of $i$-th final user (°C)
- $M_{FU,i}$: mass of the water in the heating body at $i$-th final user (kg)
- $k_s$: overall heat transfer coefficient from the heating body to the ambient air at the final user (W/(m² K))
- $A_{3,i}$: surface area of the heating body at the $i$-th final user (m²)
- $v_{A,i}$: temperature of the ambient air at the $i$-th final user (°C)
- $M_{A,i}$: mass of the ambient air at the $i$-th final user (kg)
- $c_A$: specific thermal capacity of the ambient air (J/(kg K))
- $τ_{wp}$: convective heat transfer coefficient from ambient air to the inner side of building’s wall (W/(m² K))
- $A_{BL,i}$: surface area of the building’s walls at the $i$-th final user (m²)
- $v_{BL,i}$: temperature of the inner side of building’s wall at the $i$-th final user (°C)
- $M_{BL,i}$: mass of the building’s walls at the $i$-th final user (kg)
- $c_w$: specific thermal capacity of the building’s wall (J/(kg K))
- $k_{wp}$: heat transfer coefficient from the inner side of building’s wall to the environment at the final user (W/(m² K))
- $v_{R,i}$: temperature of the water in the $i$-th return pipe (°C)
- $M_{R,i}$: mass of the water inside the $i$-th return pipe (kg)
- $m_{R,i}$: mass flow in return pipe (kg/s)
- $τ_{w,i}$: temperature of the water at the exit of $i$-th mixing node (°C)
- $τ_{PT}$: overall heat transfer coefficient from the water inside the return pipe to the environment (W/(m² K))
- $A_{R,i}$: area of the $i$-th return pipe (m²)
- $Q_{vec}$: accumulated energy within district heating pipeline network (J)
- $Φ_{DH}$: heat flux delivered to the pipeline network (W)
- $Φ_{FU,i}$: heat flux delivered to the $i$-th final user (W)
- $Φ_{loss}$: heat loss to the environment (W)
- $Δt$: period of time (s)
- $FU_i$: $i$-th final user
- $MP_i$: $i$-th mixing point
- $TN$: delay time (h)
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