



Article Technical Feasibility Assessment for a Novel Fifth-Generation District Heating Model of Interconnected Operation with a Large-Scale Building

Young-Jik Youn¹ and Yong-Hoon Im^{2,*}

- ¹ Energy Efficiency Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 34129, Korea
- ² Department of Mechanical System Engineering, Sookmyung Women's University, 100 Cheongpa-ro 47-gil, Yongsan-gu, Seoul 04310, Korea
- * Correspondence: iyh@sookmyung.ac.kr; Tel./Fax: +82-2-710-9489

Abstract: In this study, a novel fifth-generation district heating (DH) model was proposed that implements the energy-prosumer concept of bilateral heat trading (BHT) process between the DH network and the building. The newly proposed BHT model can be characterized by the feature of using the low temperature of DH return pipe's water. The technical feasibility of the proposed BHT model was evaluated through operation simulation analysis based on the actual operation data of the hybrid pilot system combined with the fuel cell and heat pump and the annual hourly temperature profile of the existing DH return pipe. The main objective of this study is to examine the technical feasibility of the interconnection operation model with the existing DHN as an alternative to overcome the limitations of the current fuel cell cogeneration model, which suffers from the low production volume caused by the high initial investment cost. From the simulation results, it was confirmed that considerable operational benefit, more than 30% in terms of primary energy savings, can be achieved with the proposed model, and compared to the stand-alone model of the fuel cell cogeneration system for the building, it can provide a more flexible technical environment to improve the system utilization rate by about 40%.

Keywords: bilateral heat trade model; fifth-generation district heating; fuel cell; low-exergy heat source; heat pump

1. Introduction

A variety of sustainable district heating and cooling (DHC) models are being proposed in responding to increasingly stringent regulations on the use of fossil fuels to achieve the "Carbon Neutral 2050" target [1-3]. Nevertheless, the existing large-scale combined heat and power-based DHC model is expected to maintain its vested interests in the market for the time being due to the economy of scale and the low economic feasibility of renewable energy technologies. In addition, the problem of power grid resilience due to the deepening of natural disasters caused by climate change is expected to have a positive effect on securing the market competitiveness of the DH model [4]. However, the rapid transition to a distributed energy generation platform will bring about a major change in the industrial ecosystem related to the DHC market. The DHC model is receiving great attention for its inherent great potential to evolve into a smart thermal energy network in response to the rapidly changing business environment due to climate change. Despite the fact that replacing traditional fossil fuel-based efficiency-centered energy systems with renewable energy based sustainability-centered systems is the most obvious countermeasure to addressing the threat of climate change, it is necessary to recognize the fact that there is still a large gap between the ideal and reality in terms of achieving the carbon-neutral target by 2050. In this regard, a new variant of the DH model in which the energy-prosumer concept is



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). applied, namely the 5GDH model, is receiving great attention as a promising alternative to building a carbon-neutral DHC platform, and its application to the DH sector is being actively promoted [5–9]. H. Lund et al. [6] identified differences and similarities between fourth-generation DH (4GDH) and 5GDH regarding aims, and abilities and have shown that 5GDH has been focused on combined heating and cooling, using a collective network close to ambient temperature levels as a common heat source or sink for building-level heat pumps. H. I. Topal et al. [7] conducted the energy, exergy, and thermos-economic analysis of a CHP-based DH system and have shown that lowering the operating temperatures increased the energetic and exergetic efficiencies of the CHP-supplied DH system simultaneously. J. Lindhe et al. [8] reviewed the status and outlook for shared energy systems and 5GDH and identified existing research gaps and challenges that need to be addressed in the further development of 5GDH. In consideration of the representative feature of 4GDH and 5GDH models, i.e., low operating temperature, heat pumps can be said to be the key facility and the power-to-heat (PtH) model will certainly play an important role in building a new DH platform in the future. Unlike the electrification-based PtH model that is suitable for the existing DH model called the third-generation DH model, another PtH model based on the heat pump is definitely applicable to the 4GDH or 5GDH models. Given the unique properties of the 4GDH model, aiming at introducing more renewable heat into the district heating network (DHN) [10], the application of the PtH model in line with the 4GDH or 5GDH models can greatly contribute to alleviating the current issues of the operational instability of the power grid caused by the abrupt expansion of new and renewable energy supply. Reflecting this aspect, the 4GDH model based on a large-capacity heat pump is rapidly being commercialized, mainly in Nordic countries [11,12]. As is well known, the 5GDH model is emerging as one of the promising technologies in relation to the carbon-neutral DH platform [5,9]. Even though there is some debate about the technical relevance between the 4GDH and 5GDH models [6], the 5GDH model is attracting great attention in that it can perform a key function to realize a smart thermal energy network through bilateral energy transaction between the DHN and the building. The low supply temperature condition of the 5GDH model, around 15 °C, has the great advantage of not only greatly improving the range of usable heat sources, but also providing an operating environment where actual heat trading between parties to the heat transaction can occur. Furthermore, in applying the PtH model, it is possible to increase the supply temperature by adjusting the supply temperature according to the customer's needs of heat demand, providing huge operational flexibility, which in turn can achieve significant market penetration of the model [13–15]. When considering the next-generation DH model linked with PtH technology, the aspect of utilizing surplus renewable power has been mainly emphasized, but the aspect of improving thermal efficiency according to various heat sources for heat pumps is often overlooked. F. Calise et al. [16] presented the dynamic simulation model and thermos-economic analysis of a 5GDH, which uses seawater as a thermal source, and bidirectional low-temperature neutral rings were investigated in which the temperature of the working medium is controlled by means of two groups of heat pumps cooled by seawater. A. M. Joderir et al. [17] reviewed the challenges confronted by the 4GDH model associated with the exploitation of solar thermal, waste heat, geothermal, and biomass energy sources into district heating systems, and it was revealed out that low-temperature waste heat and low-enthalpy geothermal sources inevitably require the application of heat pumps.

From the viewpoint of improving the operational performance of heat pumps, not the system efficiency at the rated operating condition, it would be interesting to make a consideration of the technical feasibility of the model that uses the DH's return pipe hot water as a heat source for the heat pump, instead of the existing available various heat sources such as geothermal or air sources [18–21]. Henrik Pieper et al. [18] performed an analysis on how hourly temperature variations of different heat sources influence the overall coefficient of performance (COP) of heat pumps associated with DH and the optimum capacities of heat pumps depending on the types of heat sources, groundwater, seawater, and air

source, has been reported. J. Barco-Burgos [19] has reviewed different DHC networks on which various heat pump system configurations were implemented into DHC systems and examined the PtH model as a cost-effective measure that can contribute to fossil fuel substitution. A. Arabkoohsar et al. [20] proposed an integrated DHC system to address the problems of too low summer demand and temperature at the consuming sides and revealed that challenges of the high amount of waste disposal, low velocity of hot water in district heating pipelines, and the high amount of waste heat can be alleviated to some extent. However, most of the literature has focused on the aspect of improving DH operating performance by adopting heat pumps based on various low-temperature heat sources within the boundary of the DHN, rather than considering interactions with more diverse elements to be connected with the DHN, as will be dealt with in this study. Considering the bilateral heat trading (BHT) model with the existing DHN, the model with other DHNs with similar heat demand patterns and operating temperature can be postulated not to be able to achieve the expected effect in practical terms. Therefore, in this study, a new concept of the BHT model between a building, in which a kind of distributed power generation system is installed, and the existing DHN is proposed. Moreover, by reflecting the current market demand to cope with the threat of climate change, it is designed to apply the fuel cell system as a prime mover for the distributed power generation system since the fuel cell (FC) cogeneration system (CGS) has been also attracting keen attention as a promising alternative to attain carbon neutrality in future [22–24]. A. Alns et al. [22] have performed the feasibility study of a solid oxide fuel cell (SOFC)-based CGS in the application for an office building in Qatar. H. R. Ellamla et al. [23] reviewed the current status of FC CGSs applied in the residential sector and have shown that FC CGSs are the most beneficial and promising technology for the cogeneration model in the future; however, they also indicated the main disadvantage of high initial investment cost as the main cause of low production volume. F. Accurso et al. [24] presented the technical and economic feasibility of the introduction of an SOFC-based cogeneration system to supply non-residential buildings with electricity and heat and have shown that, despite the current high investment cost of the SOFC system, the option is yet advisable if supported by effective subsidies, and it could offer a competitive alternative to traditional systems, especially in the hospital sector.

As can be noticed from the current trends in the energy market, it is worth noting that the FC technology and the relevant market are also rapidly growing as the various support mechanisms and policies including subsidies for new and renewable energy are accelerated, riding on the carbon neutrality issue. Although the FC CGS has achieved remarkable improvement in terms of technical performance and system durability, self-sustainability in terms of the economy as a stand-alone model has not been attained yet. Therefore, for the time being, it is necessary to seek alternative business models in connection with other technologies, and interconnecting with the DHN, as proposed in this study, can be a good alternative to meet the need. In that sense, it should be noted that other CGSs using fossil fuels are excluded from the consideration of this study. Nevertheless, it should be noticed that CGSs have long been applied in various fields, including the building sector, due to their advantage in terms of operational efficiency against separate heat and power methods, and are still regarded as an effective measure to cope with climate change [25,26]. Although there are skeptics about the role of CGSs in the coming climate change era, fossil fuel-based CGSs are still expected to play a role as a bridge technology to fill the gap until renewable energy technology can secure economic competitiveness in the market.

On the basis of the aforementioned knowledge gap with regard to the efficient operation of heat pumps in terms of utilizing the low exergy level of heat sources, which has been overlooked compared to the power grid instability problem, the main objective of this study is to examine the technical feasibility of the interconnection operation model with the existing DHN as an alternative to overcome the limitations of the current fuel cell cogeneration model suffering from the low production volume caused by the high initial investment cost. In particular, the aspect of heat utilization with low exergy is emphasized by proposing a model in which the hot water of the DH return pipe is used as a heat source for the heat pump and the DH return pipe is used as heat storage for fuel cell waste heat. In this framework, this study consists of four main sections: model description in Section 2, operation simulation and performance analysis in Section 3, discussions based on simulation results in Section 4, and conclusions in the last section.

2. Model Description

Figure 1 shows the illustrative diagram of the proposed BHT model between the district heating network (DHN) and a building. The heat from the heat pump using a low-temperature heat source of DHN return pipe can be supplied to meet the part of the heat demand of a building. Conversely, the waste heat recovered from the FC CGS installed in the building is utilized to make up for the temperature drop of the DHN return pipe. It is noted that the heat trading process between the stakeholders, i.e., the DHN and the building, does not necessarily occur simultaneously.



Figure 1. Illustrative diagram of the proposed BHT model between the DHN and a building.

A portion of the DHN return pipe hot water can be branched and supplied to the primary side of the heat exchanger, and a circulation loop constituting the evaporator of the heat pump is established on the secondary side of the heat exchanger. The surplus heat from the FC CGS can be utilized to reheat the DHN return pipe's hot water to compensate for the reduction of the working potential of the hot water caused by operating heat pumps and, on the other hand, it can be regarded as a heat storage process to the DHN return pipe. The sensible heat energy of the DHN return pipe's hot water can be of great interest due to its suitable operating temperature range for being used as a heat source for heat pumps instead of using other low temperature range heat sources such as air, water, or geothermal heat.

Figure 2 shows an example of the annual operating temperature profile of supply and return pipes of the existing DHN. It is noted that, in summer, the supply temperature is regulated to not exceed 85 °C in response to the decrease of heating demand, so the temperature difference between the supply and return pipes is observed to be abruptly reduced as well. It is noteworthy that the accessibility of the DHN return pipe can be estimated to be superior to other alternative heat sources except for the air heat source. In this regard, the technical feasibility of the newly proposed DH model needs to be investigated in detail as follows.



Figure 2. The annual operating temperature profile of supply and return pipes of the existing DHN.

2.1. Modeling of Heat Pump System

In order to conduct an operating simulation analysis for the technical features of the proposed BHT process between the DHN and the building, it is necessary to model the key equipment such as heat pumps and the operating process. However, it needs to be noted that a lot of simplifications or assumptions were applied to secure the reliability of the analysis results or minimize the uncertainty that arises from the rigorous modeling approach such as cycle simulation when field operation data or empirical information on operating performance are available.

Figure 3 is the schematic diagram of the FC CGS connected to the DHN via heat pumps. It is different from the model proposed in this study in that it was installed as one of the DH energy generation facilities rather than installed in the building as a distributed generation system. It is noted that, as shown in Figure 3, the process heat of the PEM fuel cell system is being recovered in two stages at different temperature ranges. That is, the high-grade heat is being recovered in one part of the FC CGS involved in the direct heating of return water of the DHN up to 110 °C and the low-grade heat is also being recovered to be supplied to the heat pumps to attain about a 15 °C temperature difference at the condenser side of heat pumps.

The technical specifications and the operating performance data of the reference FC CGS and HP hybrid system in rated operating conditions are summarized in Table 1 and it is shown that a good operational performance of heat pumps, about 5.9, was achieved in actual operating conditions.



Figure 3. Schematic diagram of the FC CGS connected to the DHN via heat pumps.

Table 1. Technical s	specification and the	operational	performance	data of the re	eference I	FC CGS a	ind
HP hybrid system.							

	Unit	Designed Value	Operating Value
Evaporator inlet temp.	°C	60	51.7
Evaporator outlet temp.	°C	32	29.3
Condenser inlet temp.	°C	55	51.3
Condenser outlet temp.	°C	70	64.8
Mass flow rate for cooling medium (evaporator side)	m ³ /h	230	250
Mass flow rate for DHN (condenser side)	m ³ /h	100	112.6
Rated power of compressor	kW	770	664
СОР	-	5.23	5.9
Heating capacity of heat pump	RT	1145	1110

2.2. Modeling of Heat Trade Process

In the modeling of the BHT process, the heat supplying process to the heat pump can be simply modeled as a heat exchanger design problem with the ε -NTU method in that the outlet temperature of the DH return pipe via a heat pump evaporator and the corresponding heat transfer rate is to be determined with the prescribed mass flow rates in the DHN return pipe and evaporator of the heat pump. The conventional ε -NTU method was implemented in the simulation to select the appropriate size of the shell-and-tube type heat exchanger, and the ε -NTU relationship for this is shown in Figure 4. It is assumed that the heat exchanger system operates with the following condition,

$$\dot{m}_{DH} \ge \dot{m}_{HP}$$
 (1)



Figure 4. *ε*–NTU relations for shell and tube HEX (single pass).

The heat capacity rates can be determined as follows [27],

$$C_{HP} = \dot{m}_{HP} C_{p,HP} \tag{2}$$

$$C_{DH} = \dot{m}_{DH} C_{p,DH} \tag{3}$$

$$C_{min} = min(C_{HP}, C_{DH}) = C_{DH}$$
(4)

$$C_{max} = max(C_{HP}, C_{DH}) = C_{HP}$$
(5)

Heat capacity ratio, effectiveness, and the number of transfer units (NTU) can also be given as,

. ...

Heat capacity ratio:

$$C_r = \frac{C_{min}}{C_{max}} = \frac{C_{DH}}{C_{HP}} \quad (0 < C_r \le 1)$$
(6)

Effectiveness:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{max}} = \frac{C_h(T_{h,i} - T_{h,o})}{C_{min}(T_{h,i} - T_{c,i})} = \frac{C_c(T_{c,o} - T_{c,i})}{C_{min}(T_{h,i} - T_{c,i})}$$
(7)

The number of transfer units:

$$NTU = \frac{UA}{C_{min}} = \frac{UA}{\left(\dot{m}C_p\right)_{HP}}$$
(8)

The useful formula for heat exchanger design problems of NTU and ε is expressed as [27],

NTU
$$(\varepsilon, C_r) = \frac{\text{UA}}{C_{min}} = \frac{-1}{\sqrt{1+C_r^2}} ln\left(\frac{\frac{2}{\varepsilon_1} - 1 - c - \sqrt{1+c^2}}{\frac{2}{\varepsilon_1} - 1 - c + \sqrt{1+c^2}}\right)$$
 (9)

In this modeling, since the COP is fixed by applying the rated operating conditions of the heat pump, the power consumption of the heat pump and the amount of heat supplied to the building can also be easily determined. The other heat-supplying process, from the FC CGS to the DHN return pipe, can be modeled simply without considering the detailed heat exchanging process as in the case of heat pumps. In this study, two operation modes in the management of the FC CGS are to be adopted for the assessment of the technological feasibility of the proposed model, i.e., heat load or PLTO mode. In PLTO mode, it is assumed that the FC CGS is operated according to the energy load condition of the building, not depending on the operating condition of the DHN. On the contrary, in the heat load tracing operation (HLTO) mode, the FC CGS operation is to be regulated not to generate extra surplus heat to be supplied to the DHN. Results for the different operating modes of the FC CGS on the operating performance of the BHT model are described in detail below. The overall simulation procedure including heat exchanger design and operation is presented in Figure 5.



Figure 5. Overall simulation procedure including heat exchanger design and operation.

Figure 6 shows the example of the simulation results for the profile of heat exchanger performance which is evaluated by using Equations (1)–(9).



Figure 6. Simulation results for the profile of heat exchanger performance.

3. Operation Simulation and Performance Analysis

3.1. Building Load Forecasting

Despite the technical feasibility of the 4GDH model to respond to climate change, the main reason that the market is struggling is economic feasibility due to low heat demand density. The proposed model aims to have the characteristics of the 4GDH model that utilizes low-temperature heat and the characteristics of the third-generation DH model that is easy to apply to buildings with high heat demand density. Additionally, it is the BHT mechanism that makes it possible. To verify this hypothesis, in this study, a large-scale complex was considered as a new heat demand for connection with DHN. In this study, the new building's energy loads were estimated using the energy load prediction module of the dynamic driving simulation tool developed in the previous study. Figure 7 shows the example of the hourly unit energy load model by month per unit floor area [28]. The annual hourly energy load profiles can be established by synthesizing the hourly unit energy load model and daily energy load data [29].

To anticipate the energy load from the total floor area input, daily and hourly energy load distribution patterns per unit floor area are required according to the types of buildings. The total floor area of the target building of the simulation is 634,684 m², and it consists of various types of buildings as given in Table 2. Using the data of total floor area according to the types of building in Table 2, the energy loads of the target building can be finally forecasted in units of one hour throughout the year since the daily and hourly energy load distribution patterns per unit floor area has already been predetermined in previous studies. In other words, in the energy load forecasting process, the data required to obtain the distribution of the load data by time of year are simply the data of the total floor area for each building, as given in Table 2, which can be seen in Figure 8. For more detailed information on this, please refer to the related literature [28,29].



Figure 7. Hourly unit energy load model by month per unit floor area.

Table 2.	Floor	area	for t	the	types	of	buildings	s of	the	complex	buildings	•
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Build. Type	Department Store	Officetel	Office	Exhibition	Shopping Center	Hotel
Floor area (m ²)	79,422	100,195	114,228	106,029	155,235	79 <i>,</i> 575

The energy loads anticipated above are summarized in Table 3. The total annual cooling load of the building is 129 GWh and the maximum is 127 MWh. This shows that the target building of this study has the load characteristics of a large commercial building centered on a huge cooling load, which can be definitely differentiated from the low heat demand density for the existing 4GDH model.

Table 3. Summary for annual energy loads of the building.

	Heating	Cooling	Power
Max (MWh)	76.8	127.4	19.7
Total (GWh)	71.3	129	81.5



Figure 8. Forecasted energy load profile of the target building. (**a**) Overall annual hourly heating load of the building. (**b**) Overall annual hourly cooling load of the building. (**c**) Overall annual hourly power load for the building.

3.2. Operational Simulation of BHT Process

As shown in Figure 1, the recovered heat from the FC CGS is designed to be supplied to the DHN return pipe, just as the DHN is used as an auxiliary heat storage facility, so that the waste heat of the cogeneration system is not wasted even if there is no heat demand of the building in real time. An alternative is to supply the recovered heat from the FC CGS directly to the building, but it is not preferred to the proposed model due to the technical and economic inefficiency caused by the discrepancy between heat supply and demand that inevitably occurs in the real-time operation management of the CGS, not to mention the economic burden of additionally installing a heat storage tank in the building. In the proposed model, it is assumed that the recovered heat from the FC CGS is solely used to reheat the DHN return water unlike the reference case as shown in Figure 3, in which the recovered heat was utilized in two stages as described previously. It should not be overlooked that the supply of heat from the DHN return pipe to the heat pump and the reheating process by the FC CGS do not necessarily occur simultaneously. It is also noted that the actual operation data of the existing DHN was utilized instead of relying on a theoretical analysis in order to secure the reliability of the analysis result. In particular, the mass flow rate, temperature of the DHN return pipe, and the heat supply data from incineration to the DHN, etc. were used as inputs for the simulation.

In this study, two operation modes are in consideration for the assessment of the performance evaluation of the newly proposed BHT model. With the HLTO mode, the FC CGS operation was assumed to be controlled so that additional heat exceeding the amount of heat supplied from the DHN to the heat pump is not generated. It is also assumed that heat supply and return settlements between the operators of the DHN and the building are performed on a daily basis. On the contrary, as an alternative to implementing the BHT process, the power load tracing operating (PLTO) mode in which the FC CGS is driven at full load conditions regardless of the building's heat demand conditions will also be analyzed. In terms of practical applicability, the PLTO mode can be regarded as more practical given the ease of control. However, it is worth noting that the connection with the DHN ensures a stable heat supply for the operation of the heat pump compared to its stand-alone operation, regardless of the applied operation modes.

For the sake of simplicity of the analysis, in this study, it is assumed that the heat supplied from the incinerator to the DHN is not involved in the heat trading process during periods of high heat demand, such as winter, although the heat from the incinerator cannot be accurately determined under actual operating conditions. On the other hand, in periods of low heat demand such as summer, the heat source for the heat pump operation is assumed to be solely covered by the heat supplied from the incinerator to the DHN. This means that the operation of the FC CGS is not economically feasible at all due to the lack of heating load in summer, so, during periods of low heat demand from the building, the operation of the FC CGS is limited, as illustrated in Figure 9. Creating more heat demand, such as heat-driven cooling, is clearly a desirable operating condition from the point of view of the BHT model.



—PLB —Incinerator

Figure 9. Annual profile for the heat productions and the illustration of the FC CGS operation.

3.2.1. Operational Mode I: Heat Load Tracing Operation (HLTO) Mode

In simulating the BHT process between the existing DHN and a building, the FC CGS capacity is the main design factor that determines the maximum amount of heat that can be supplied to the DHN return pipe. Figures 10 and 11 show the annual hourly heat generation profile to meet the building's heat demand and the corresponding heat source utilized for generating heat via the heat pump according to different system design conditions. When the heat pump's capacity is designed to be doubled with the FC CGS capacity being fixed, as shown in Figures 10 and 11, it is shown that the demand when a heat source for operating heat pumps exceeds the maximum heat supplying capability from the FC CGS, Q_{fc}^{max} , is to be supplied from DHN return pipe, which is indicated by Q_{res_aux} . The heat from the incinerator is denoted by Q_{incin} and, as mentioned previously, it is assumed to be only involved in the period of low heat demand of the building. From the simulation results shown in Figures 10 and 11, it is noticed that as the number of heat pump units is increased from 2 units to 5 units while FC CGS capacity is fixed, Q_{hex} , which denotes the heat supply from the heat source, and W_{comp}, denoting power consumption of heat pumps, increase correspondingly. However, the heat supply from the DHN return pipe to the evaporator of heat pumps abruptly increases as well because the heat demand for heat pumps exceeds the maximum heat-supplying capacity from the FC CGS.



Figure 10. Profile of the heat supply (**top**) and the heat source for heat pumps (**bottom**) for HLTO mode (HP: 2 units, FC: 7 units).



Figure 11. Profile of the heat supply (**top**) and the heat source for heat pumps (**bottom**) for HLTO mode (HP: 5 units, FC 7: units).

The heat balance between the main operating variables with regard to the operation of the heat pump can be given by Equation (10),

$$Q_{hex} = Q_{fc} + Q_{res_aux} + Q_{incin} \tag{10}$$

In HLTO mode for the FC CGS, the terms constituting Equation (10) can be summarized as shown in Table 4 according to the applied assumptions described above. For example, as can be seen in Table 4, Q_{incin} is set to zero in the period of high heat demand from the assumption that it is not involved in heat pump operation. Meanwhile, Q_{fc} is assumed to be zero with the condition that the FC CGS is not being operated due to economic considerations.

Table 4. Summary for the heat balance among the main operating variables of the heat pump operation.

	Q_{fc}	Q _{res_aux}	Qincin	Cf.
0	0	Qres_aux	+ Q _{incin}	Summer
Q_{hex}	$Q_{fc} + Q_{res_i}$	ıux	0	Winter

In the period of low heat demand in the building, e.g., summer, it can also be conceived that Q_{incin} is sufficient to cover the heat demand for operating heat pumps. As a result, Equation (10) can be further simplified as follows,

(

$$Q_{hex} = Q_{incin} \tag{11}$$

It implies that, in the period of low heat demand, all the heat for heat pumps is solely covered by the heat of the incinerator. As we will see later in the next section, RPES, a representative indicator of operational efficiency, has the highest value during this period.

In the period of high heat demand in the building, e.g., winter, the heat demand for heat pumps can be supplied from the DHN or the FC CGS, as shown in Equation (12)

$$Q_{hex} = Q_{fc} + Q_{res_aux} \tag{12}$$

where Q_{hex} can be calculated when Q_{load} is determined under the assumption that heat pumps are operated with rated conditions as in this study, from the following relation for heat pumps,

$$Q_{hex} = \frac{Q_{load} \times (1 - COP)}{COP}$$
(13)

The recovered heat from the FC CGS can also be determined with the following relations,

$$Q_{fc} = Q_{hex} \text{ (if } Q_{hex} \le Q_{fc}^{max}) \tag{14}$$

$$Q_{fc} = Q_{fc}^{max} \left(\text{if } Q_{hex} > Q_{fc}^{max} \right)$$
(15)

Therefore, in practical terms, the heat flow from the FC CGS to the DHN cannot occur in case HLTO mode is applied as can be verified in Figures 10 and 11. For example, if the amount of heat required to operate the heat pump exceeds the maximum heat capacity of the FC CGS, the remaining heat demand for the heat pump is covered by the DHN.

Figure 12 shows the overall heat supply and demand trend with HLTO mode as the number of heat pump units, i.e., the installed capacity of the heat pump, increases for a fixed FC CGS capacity. It can be noticed that there is no heat flow from the FC CGS to the DHN, as previously explained, which increases the amount of heat supplied from the DHN to the heat pump as the heat demand for heat pumps is increased.



Figure 12. Overall heat supply and demand trend with the HLTO mode (FC CGS capacity is fixed).

The operating characteristics of the BHT process for inverse conditions, i.e., a fixed heat pump capacity with the variable capacity of the FC CGS, are also shown in Figure 13. It can be seen that as the heat supply capacity of the FC CGS increases, the ratio of heat supply from the DHN to the heat pump decreases correspondingly, but there is still no heat flow from the FC CGS to the DHN. Therefore, the HLTO mode can be characterized as a rather conservative operating strategy, which makes it difficult to fully reflect the advantages of the BHT model, although the settlement of heat transactions between stakeholders can be resolved relatively easily.



Figure 13. Overall heat supply and demand trend with the HLTO mode (heat pump capacity is fixed).

3.2.2. Operational Mode II: Power Load Tracing Operation (PLTO) Mode

As an alternative way of implementing the BHT process, PLTO mode can be adopted in which the FC CGS is driven regardless of the heat demand condition of heat pumps. The DHN can serve as a heat storage facility for surplus heat generated from the FC CGS, providing an opportunity for attaining more efficient utilization of the recovered heat by supplying it to other buildings that were connected to the DHN. Figures 14 and 15 show the annual operating characteristics of the system with the PLTO mode, in which annual hourly heat production behavior meets the building's heat demand and the heat source required to run the heat pumps. Contrary to the results of the HLTO mode, it is revealed that heat flow from FC CGS to DHN is being realized under the condition of low heat demand, where the amount of recovered heat from the FC CGS exceeds that of heat required for operating the heat pumps. It can be clearly seen that the larger the FC CGS capacity, the more heat flow to the DHN is generated. As can be seen in Figures 14 and 15, most of the heat recovered from the FC CGS is still used for compensating for the heat that has been consumed for the operation of heat pumps. As the building's heat demand gradually decreases, the surplus heat remaining even after compensating for the heat pump usage can eventually be supplied to the DHN return pipe, which has been marked with negative values to differentiate them from the heat used for buildings. It is also noted that the increased heat supply capacity of the FC CGS consequently reduces the amount of heat usage from the DHN return pipe for operating the heat pumps in periods of high heat demand in the building.



Figure 14. Cont.



Figure 14. Profile of the heat supply (**top**) and the heat source for heat pumps (**bottom**) for PLTO mode (HP: 2 units, FC: 14 units).



Figure 15. Cont.

18000





Figure 15. Profile of the heat supply (**top**) and the heat source for heat pumps (**bottom**) for PLTO mode (HP: 4 units, FC: 14 units).

Figure 16 shows the operating characteristics of the proposed system in terms of heat balance with the PLTO mode in which the FC CGS capacity was set to be 5.6 MW and the number of heat pumps is changed. For low heat pump capacities, i.e., for one or two sets of heat pump units, the amount of the waste heat from the FC CGS is large enough to meet the heat demand of the heat pump and the excess heat is supplied to the DHN. The heat flow from DHN to heat pumps is not necessary. As the heat pump capacity increases by more than five sets, it is interesting to note that the heat supply from the FC CGS to the DHN is fixed, whereas the heat supplied from the DHN to the heat pump gradually increases despite the presence of excess waste heat of the FC CGS. These operating characteristics can be attributed to the temporal discrepancy in real time between the heat demand of the building and the heat-supplying capability of the FC CGS. Therefore, it should not be overlooked that the FC CGS capacity design will be greatly limited if the BHT is not taken into account as being considered in this study, since the amount of heat supplied to the DHN as shown above via connected operation mode has to be discarded as waste heat with the stand-alone operation.

Figure 17 shows the operating characteristics of the BHT process for inverse conditions, i.e., variable capacity for the FC CGS, and fixed heat pump capacity, for the PLTO mode. It is shown that the heat from the DHN to heat pumps gradually decreases as the installation capacity of the FC CGS increases. It is not difficult to predict that the heat flow from the FC CGS to the DHN will increase monotonically, while the heat supplied from DHN to the heat pump will decrease. Ultimately, the heat supply from the DHN to the heat pump approaches zero as the FC CGS capacity exceeds the demand from the heat source required to operate the heat pump. However, in practical terms, a simple approach to increase the FC CGS capacity is not acceptable in terms of economic feasibility, as will be studied in future studies.



Figure 16. Overall heat supply and demand trend with the PLTO mode (FC CGS capacity is fixed).



Figure 17. Overall heat supply and demand trend with the PLTO mode (heat pump capacity is fixed).

4. Discussions

Even though it can be expected that excellent energy saving can be achieved with the newly proposed BHT model, it is necessary to verify the quantitative performance of the model according to the applied operation mode and various operating environments. In this study, the RPES has been evaluated to quantify the technical operation performance of the newly proposed bilateral heat trade model, and the schematic diagrams of the RPES



evaluation procedure according to the adopted operation mode of the FC CGS are shown in Figure 18.

Figure 18. Schematic diagrams of the RPES evaluation procedure according to the adopted operation mode. (**a**) HLTO. (**b**) PLTO.

In the evaluation of the RPES for the BHT model, unlike the case of the CHP-based DH model, it can be seen that there is a trade-off relationship between the heat flow from the DHN to the building through the heat pump and the heat flow from the FC CGS to the DHN when the building's heat demand is high. Meanwhile, the heat flow from the DHN to a building in a low heat demand period, mainly in summer, can be estimated to exert a positive contribution to RPES since only the heat from the incinerator is assumed to be involved in this period as mentioned previously.

The detailed annual hourly RPES profiles according to the applied operational modes, i.e., heat or PLTO mode, are shown in Figure 19. In the case of HLTO mode, the overall RPES was evaluated to achieve approximately 15%. As shown in Figure 19a, a maximum of 61% is achieved in the period when the heat demand of the building is low, but decreases to 26% in the period when the heat demand is high. In the case of power load tracing mode, as shown in Figure 19b, a more efficient operational performance, RPES, was found to be achieved. The overall RPES is estimated at 22%, which is approximately 30% higher than

the heat load tracing mode, with a peak hourly RPES of approximately 35% during periods of high heat demand. The improvement in RPES by applying the power load tracking operating mode is due to the increased utilization of the FC CGS through the bilateral thermal trading operation.



Figure 19. Annual hourly RPES profile according to the applied operational modes. (**a**) HLTO. (**b**) PLTO.

The sensitivity of the proposed BHT model to different heat pumps and the FC CGS capacities and the COP of the heat pump has been conducted, and the analysis results are shown in Figures 20 and 21 according to the applied operation modes. The RPES of the proposed model over SHP tends to decrease monotonically with the increasing capacity of heat pumps using the DHN return pipes, irrespective of the FC CGS capacity level.



Figure 20. Sensitivity for different heat pumps and the FC CGS capacities and the COP of the heat pump. (**a**) HLTO mode with COP 5.9. (**b**) HLTO mode COP 3.5.



(a)



Figure 21. Sensitivity for different heat pumps and the FC CGS capacities and the COP of the heat pump. (a) PLTO mode with COP 5.9. (b) PLTO mode with COP 3.5.

One of the main reasons why the RPES decreases as the capacity of the heat pump increases is that the current DHN adopted in this study is mainly composed of PLB, not CHP, as a heat source as mentioned above. Therefore, the heat from the DHN return pipe to the heat pump does not have a positive effect on the RPES evaluation. If the CHP-based DH model is considered as the existing DHN in the analysis, instead of the current PLB-based DHN, a more improved level of RPES achievement can be certainly attained to that amount of CHP's contribution over SHP. However, the degree of detailed contribution is somewhat complicated depending on the operating conditions of CHP and connected operation with the other DHN including renewable heat source connection, so it will be considered through future research.

Figure 22 shows the sensitivity analysis results of RPES and heat pump power consumption versus heat pump COP variation for a specific system configuration with 10 units of the heat pump with 1100 RT and 7 units of the FC CGS with 500 kW_{th}. As in the previous results of Figures 20 and 21, the RPES showed a tendency to monotonically decrease as the COP of the heat pump decreased, which can be attributed to an increase in power consumption of the heat pump, as shown in Figure 22. In addition, it is shown that in the case of the PLTO mode, the operating performance degradation rate for a given COP change is about 32%, whereas, in the HLTO mode, it causes a performance degradation of 59%. Therefore, it can be demonstrated from the simulation analysis that PLTO mode is preferable to HLTO mode in terms of securing operational stability.



Figure 22. RPES and heat pump power consumption profile for heat pump COP variation.

From the aforementioned simulation-based analysis results of the BHT model between the existing DHN and a building, some major technical issues can be presented as follows. First, the proposed model can be evaluated as a hybrid model in which various DH generation models, from the third to fifth generation, have been reflected. It aims to create large-scale new heat demand for the building utilizing the infrastructure of the third generation DH model, but, at the same time, using a low-temperature heat source of DHN return pipe via heat pumps, and adopts the interactive heat trading process with the building as a prosumer. In the case of buildings to be simulated, the actual construction plans and data of the building being promoted near the actual target DHN have been referred for ensuring more realistic technical feasibility for which annual peak energy loads were estimated to be 76.8 MW for heating and 127.4 MW and 19.7 MW for cooling and electricity, respectively, and this corresponds to about 3% of the total demand of the existing DH system, assuming that the building's heating demand is covered solely by the DHN. From the analysis, it has been confirmed that the newly increasing heating demand can be successfully covered by the proposed model without many difficulties in terms of heat-supplying capacity and operating conditions of the existing DHN. As verified from the simulation results, the overall utilization rate of the distributed power generation system installed in the building, such as the FC CGS in this study, can be significantly improved with the connected operation with the DHN. It is also shown that the degree of enhancement of the utilization rate depends on the operation modes. For stand-alone models, e.g., SHP, the distributed power generation systems are installed and operated mainly as UPS systems due to the lack of economic feasibility caused by the absence of adequate heat demand for using the waste heat generated during operation. If the building, and consequently the distributed power generation systems, are connected with the existing DHN, the operating conditions in the management of distributed power generation systems can be changed significantly. In particular, for the PLTO mode, it has been shown that an RPES improvement of over 30% can be achieved compared to the traditional stand-alone case. In terms of closing the gap between the ideal goal such as "Carbon Neutral 2050" and the reality in the transition period of the energy sector in climate change, this highly technical operational performance of the proposed BHT model including a DHN is quite meaningful in that, recently, the RPES achievement level of the existing third generation DH model is around 22 to 25%, and it will decrease sharply in the future as the supply of renewable energy expands in responding to climate change.

In the sensitivity analysis of RPES according to the COP of the heat pump, the qualitative aspect of the heat source for the operation of the heat pump was verified as one of the key factors for securing the technological competitiveness of the proposed model. It was shown that the operating temperature of the DHN return pipe for the conventional DHN adopted in this study can provide an appropriate operating condition to meet the requirements in applying the reference fuel cell-based DH heat supply system. It was analyzed that the temperature difference before and after the heat exchanger of the heat pump evaporator can be managed within the maximum range of 10 °C, which can provide additional benefits in terms of operational efficiency for heat sources in DH systems, such as CHP plants, and reduce pipe losses from a DHN operating perspective. As a result of analyzing the sensitivity to the change in COP of the heat pump, it was confirmed that as the COP of the heat pump fluctuates at the level of 3.5 to 6.5, a deviation of about 30% from the level of the RPES may occur. This suggests that stable heat source operating conditions are important to secure the market competitiveness of the proposed model in the market dissemination stage. Although a detailed analysis was not performed on various heat sources other than the DHN return pipe in this study, it can be said that the relative superiority of the proposed application model using the DHN return pipe as a heat source for the heat pump can be indirectly confirmed via the sensitivity analysis results for varying COP and the detailed comparative analysis will be performed in further studies.

5. Conclusions

The main achievement of this study is to confirm the possibility of energy saving and operational efficiency improvement by the interconnection operation model between the existing DHN and large buildings based on field operation or empirical data for major facilities in connection with annual simulation analysis. From the analysis results, the main conclusions of this study can be presented as follows.

- Compared to the stand-alone model of the FC CGS for the building, the proposed model of interactive operation with the DHN can provide a more flexible technical environment to improve the system utilization rate by about 40%.
- In terms of the heat source management for stable and efficient operation of heat pumps, it was confirmed that considerable operational benefit, more than 30%, in terms of primary energy savings can be achieved by using the DHN return pipe hot water as a heat source for heat pumps.
- The proposed model has been proven to be quite attractive in terms of new demand development for existing DHNs, in that the new heating demand for large-scale buildings is about 3% of the existing DHN total heat demand.

More case studies are needed in various applications such as industrial, residential, and commercial buildings, as well as further studies on the economic impact of the technological advantage of the proposed model for gaining market competitiveness.

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Nomenclature

BHT	Bilateral Heat Trade
CHP	Combined Heat and Power
СОР	Coefficient of Performance
DHC	District Heating and Cooling
DHN	District Heating Network
DHN_HP	From District Heating Network to Heat Pumps
DHN_SP	District Heating Network Supplying Pipe
DHN_RP	District Heating Network Return Pipe
FC CGS	Fuel Cell Cogeneration System
FC_DHN	From Fuel Cell to District Heating Network
HLTO	Heat Load Tracing Operation
NTU	Number of Transfer Units
PLB	Peak Load Boiler
PLTO	Power Load Tracing Operation
PtH	Power-to-Heat
Q	Rate of Heat Flow (kW)
RPES	Relative Primary Energy Savings
SOFC	Solid Oxide Fuel Cell
UPS	Uninterruptible Power Supply
°C	Degree Celsius
C_r	Capacity Ratio
m	Mass Flow Rate (kg/s)
Т	Temperature of water (°C)
Greek symbols	
ε	Effectiveness

Sub(super)scripts	
aux	Auxiliary Heat (from DHN)
DH	District Heating
EVA	Evaporator
fc	Fuel Cell
HP	Heat Pump
hex	Heat Exchanger
incin	Incinerator
res_aux	Auxiliary Heat Source for Heat Pumps (from DHN)

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