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Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea

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ABSTRACT

Energy depletion and global climate change have stimulated the Korean government to strengthen energy saving and efficiency measures in all sectors. However, in industrial sector where huge energy is consumed, only small portions of the high-grade waste heat from industrial processes have been utilized by another process through industrial symbiosis networks in industrial park and large quantities of low-grade waste heat are mostly discharged into the environment. Through technological assessment of energy balance between waste heat source in industrial park and heat sink in industrial park and urban area, this study systematically develops an industrial-urban symbiosis (I-US) and conducts a co-benefit analysis for 4 scenarios. Based on the investigation on the energy utilization status of Ulsan, the scenarios for potential I-US networks are evaluated. For the supply and demand side, potential energy sources and sinks are estimated at 49,321 and 15,424 TJ/yr, respectively, noting that the demand side considered four scenarios based on the local condition analysis. Through these scenarios for the energy symbiosis networks; a reduction of 243,396 ton/yr CO2 emission and 48 million US Dollar/yr fuel cost were achieved. Due to a large transition cost for a district heating system, I-US public private partnership business model is highly recommended to attract long-term investment and institutional incentives of carbon credit and energy service companies fund are conducive to put these scenarios into practice.

1. Introduction

Industrial parks have fueled the rapid economic development and urbanization of Korea since 1962. Industrial parks, as the interface infrastructure between the resource consumption and products production, have posed various challenges and opportunities for economic, environmental and social issues at urban scale in Korea and many developing countries. To address these emerging challenges, the concept of a circular economy that applies industrial symbiosis (IS) and eco-industrial park (EIP, as a practice of IS), which focuses on the cascading and circular networking (those with geographical proximity) of resources, energy and wastes in industrial park, has been established and under global practice since early 2000 (Basu and Van Zyl, 2006; Fet, 2001; Hamner, 1996: Organisation for Economic Cooperation and Development, 2009). The industrial organization patterns the EIP which follows a circular flow model in a “resources-products-renewable resources” that serves as a major player in sustainable development (Zeng et al., 2017).

Through National EIP initiative, Ulsan city have benefited from 14 energy symbiosis networks of the high-grade heat to reduce the energy consumption and carbon emission reduction in the Onsan and Ulsan-Mipo national industrial parks (Table 1).

The energy sources and sinks of these 14 IS networks are shown in Figs. 1 and 2. The energy sources of 5 networks (#1: Yoosung to Hankuk paper, #3: Bumwoo to Korea petrochemical or GS Eco metal, #6: Sung-Am MWIF to Hysong yongyeon #2 plant and KP chemical to Korea PTG, #8: Hyundai heavy industry to Hyundai hyesco and Hyundai motors, and #12: Sung-Am MWIF to Hysong yongyeon #2 plant to Hysong yongyeon #1 plant, SKC) are the heat produced from waste incineration, and the 7 networks (#2: Korea zinc to Hankuk paper, #4: Korea zinc to Hanwon precision chemical or Yeongkwang, #7: Hansol EME to Korea PTG and Korea PTG to SKC, #9: Arkyung Petrochemical to Hanju to Evonik headwaters, #11: Taekwang petrochemical #1 to SK energy to Hysong Ulisan plant, #13: SK chemical to Hysong Ulisan, SK energy, Taekwang petrochemical #1, and #14 Lotte chemical to...
manufacturing are lost as waste heat (Johnson et al., 2008). In Turkey, 51% of the processed heat from the cement plant are wasted (Sogut et al., 2010).

To date, large quantities of low-grade waste heat, between 30 and 100 °C, are discharged into the environment by water evaporation in the industrial processes (Svensson et al., 2008; Zhang and Akiyama, 2009). Some sources of waste heat include chemical waste, waste process liquid, gaseous exhaust, and cooling media (Fang et al., 2013).

In the aspect of industrial waste heat utilization at different temperature zones, various technologies are used in the industrial and urban sectors. The supplying companies in the industrial sector produces specific quality of steam for their processes and various level of consequent waste heat. The waste heat generated is then used towards other individual companies as an energy source. The produced steam goes to the steam supply system of the demanding companies through a pipeline. For the urban sector, waste heat is utilized differently in heating and cooling purposes. Through a central heating system, the waste heat generated from each company flows to the heat management center for proper heat control. The collected heat is then supplied to the heating system of the apartment complexes or commercial building in a heat exchanger. For further improvement in the heating system, the existing individual heating system should be changed to a central heating system in order to maximize the recycling of waste heat in the central heating system mode. In the aspect of cooling, the collected heat is supplied to the cooling system of the apartment complexes or the commercial buildings going through an absorption refrigerator or a centrifugal refrigerator.

For an effective the utilization of low grade waste heat, the consideration of an urban symbiosis (US) is essential. The US as an extended concept of the IS represents an opportunity arising from a geographic proximity in the industrial and urban areas (Chen et al., 2011). The development of an industrial-urban symbiosis (I-US) can optimize the regional energy network through its sharing of infrastructures and resources (Sun et al., 2016). The I-US networks using high and low-grade waste heat is an effective measure to reduce the energy consumption and greenhouse gas (GHG) emissions. In the situation that the global society is making an effort to mitigate global warming and the energy crisis, the system design for an I-US of high and low-grade waste heat could be an important regional measure which may be sufficiently worth to consider. Fig. 3 illustrates the representation of an I-US.

A conceptual framework (Fig. 3a) of the I-US shows that heat from the industrial sector consist of a circulation of low, medium and high-pressure steam across a heat pinch for energy optimization. The combustible waste and by-product gas in the industrial sector are utilized to generate electricity. On the other hand, the waste heat from the industrial sector is supplied towards a heat management center and this is carried over as a district heat supply in the urban sector. At the urban sector, the combustible municipal waste is sent through the incinerator plant and its waste thermal heat are sent back in the industrial sector. In the incinerator plant, incineration heat is supplied towards the heat management center for proper heat control. The collected heat is then supplied to the heating system of the apartment complexes or commercial buildings through a heat exchanger.

Fig. 3b illustrates the technical concept of the I-US using low-grade waste heat in an industrial park. The industrial waste heat is processed at the 1st heat exchanger at 120 °C and goes to a 2nd heat exchanger in the heat management center at 95–115 °C. After this, heat around 95 °C goes to through pressure pump (5–7 kg/m²) in a supply header. The waste heat would go to a heat exchanger of the urban area and be pumped at 65 ± 5 °C to the public, office buildings and apartment. The waste heat at 50 ± 5 °C from the urban area will go through a heat exchanger to a return header in the pressurization facility at 3–4 kg/m² straight to a recycle pump. The waste heat is returned to the 1st exchanger at 62 ± 3 °C and comes out at 93 °C as processed waste heat.

As the high grade energy network in Ulsan city have already shown
the benefits of I-US, it is thus necessary for future planners to expand I-US networks with regards to the unused high and low-grade waste heat in the industrial complexes by applying the concept of a circular economy in terms of a cascading and recycling system.

With these circumstances, the main objective of this study is to analyze the potential of economic and environmental benefits (can be seen as co-benefits) of the designed I-US using high and low-grade waste heat. The waste heat sources are generated from the industrial complexes and available for I-US networks. A holistic integrated analytical approach (combing thermal dynamics, energy balance and spatial analysis with geographic information system) is formulated to support the analysis. A scenarios analysis is further conducted to provide practitioners feasible visions for the implementation of the designed I-US using high and low-grade waste heat sources. This research highlights as the first attempt on the potential of co-benefit of the emerging practices of I-US focusing on industrial high and low grade waste heat. To which has not yet been broadly studied and implemented in Korea.

The remainder of this paper is organized as: after this introduction section, Section 2 describes the methodologies and scenarios setting; Section 3 analyze and discusses the analytical results; and finally, Section 4 addresses the conclusions and implications.

2. Methodology

Fig. 4 illustrates the graphical representation of the overall methodological structure of the I-US based on the demand and supply of heat. High and low-grade waste heat was utilized as a potential heat source to achieve an I-US based on the demand and supply of the industrial area (industries, factories and companies) and/or urban area (residential and non-residential buildings). With heat sources and sinks information, various feasibility solution through pinch analysis and energy balance was formulated for the investigation of the I-US. Four scenarios were generated. This includes the following: (1) an expanded IS network, this considers the utilization of unused energy sources in 11 industries; (2) an US network, this considers the utilization of the energy sources in urban regions which is close to the industrial complex; (3) and (4) are expanded US networks, this considers the utilization of the energy sources in other urban regions.

Through the four scenarios, an environmental and economic assessment was conducted based on the CO2 emission and fuel cost, respectively. An implementation strategy is to be recommended to offset the problems associated to investment cost so to improve its feasibility towards putting these scenarios of I-US into its realization.

2.1. Estimation of potential heat sources in industries

The entire process flow chart is illustrated in Fig. 4. The potential heat sources for the symbiosis from the industries and/or factories in the supply side can be estimated using Eq. (1):

\[ Q_{\text{source}} = E \cdot \zeta \]  

where \( E \) is the total energy consumption in the processes of factories and \( \zeta \) is the heat recovery potential. The potential heat sources are estimated by multiplying the energy consumption by the heat recovery potential of the energy consumption.

Ulsan city does not manage the energy consumption status of all these companies but only manages the energy-consuming companies which have an annual energy consumption of more than 2000 TOE. According to the article 31 of the energy use rationalization act (Energy use rationalization act, 2014), "Any person for whom the quantity of energy consumed is at least a standard quantity prescribed by Presidential Decree, more than 2000 (hereinafter referred to as ‘excessive energy-consuming business entity’) shall report the following matters to the Mayor/Do Governor having jurisdiction over the area where the relevant energy-consuming facilities are located, by not later than January 31 each year, as prescribed by Ordinance of the Ministry of Trade, Industry and Energy: Quantity of energy consumed and products manufactured on a quarterly basis in the previous year; Estimated quantity of energy to be consumed and products to be manufactured on a quarterly basis in the relevant year; Current status of energy-consuming machinery, equipment or materials; Outcomes of the rationalization of energy use on a quarterly basis in the previous year, and quarterly plans for the rationalization of energy use in the relevant year; Current status of persons in charge of the affairs referred to in subparagraphs 1 through 4 (hereinafter referred to as “person in charge of energy management”).

Therefore, in this study, the total energy consumption is estimated by summing up the energy consumption of the high energy consuming companies in the industrial park.

McKenna and Norman (2010) established a model to estimate the industrial heat loads and technical recovery potentials for the energy-intensive industries in the UK, and concluded that about 10% of the heat load is technically recoverable (McKenna and Norman, 2010). According to the report on “Waste Heat Recovery: Technology and Opportunities in U.S. Industry”, as much as 20–50% of the consumed energy is ultimately lost during the manufacturing processes via waste heat contained in the streams of hot exhaust gases and liquids, as well as through the heat conduction, convection, and radiation from hot equipment surfaces and from heated product streams (Inc, 2008). In
Fig. 3. (a) Conceptual and (b) technical representation of industrial-urban symbiosis.

Fig. 4. Industrial-Urban Symbiosis Methodological Diagram.
this study, high grade steam recovery potential is conservatively assumed to be 5% and low grade heat in range of 100–150 °C to be 5% based on the waste heat inventory profile (Inc, 2008).

2.2. Estimation of potential heat sink

2.2.1. Industrial park

The potential heat sinks for symbiosis from the industries and/or factories in the demand side can be estimated using Eq. (2):

\[ Q_{\text{sink}} = E \eta \]  \hspace{1cm} (2)

where \( E \) is the total energy consumption in the processes of factories and \( \eta \) is the energy receiving rate. Companies located in industrial complexes want to establish energy IS networks with other companies. In the side of the industries, some potential heat sinks occur. The potential heat sinks produced from industries is estimated by utilizing the information in the survey questionnaire conducted by the Korea Energy Management Corporation (KEMCO) Busan/Ulsan branch office (A study on the expand utilization plan of surplus energy potential in Ulsan industrial complexes, 2014). The sample survey questionnaire is shown in Table S1 in the “Supporting information”.

2.2.2. Urban area

The potential heat sinks in the urban area is estimated by applying the heat load analysis procedure referring to the documentation guidelines for the proposal of the district heating system shown in Fig. 5 (The documentation guidelines for the proposal of integrated energy, 2012). Residential and non-residential buildings are selected as the target building for investigation. The apartment building complexes with more than 300 households are selected as the residential buildings. The hypermarkets, department stores, offices and hospitals are included in the non-residential buildings. The heat load analysis procedure is composed of 5 steps: 1) the estimation of gross floor area of a building, 2) the calculation of heating and cooling area, 3) the calculation of connected heat load, 4) the calculation of peak heat load, and 5) the estimation of heat demand quantity of the target region. The gross floor area of a building can be computed by multiplying the site area of an apartment house and/or building by the floor area ratio shown in Eq. (3). The heating area can be calculated by multiplying the gross floor area of a building by the heating area ratio, and the cooling area can be determined by multiplying the heating area by 0.3 (for business purposes) or 0.15 (for public purposes) shown in Eqs. (4) and (5), respectively.

\[ TFA_i = S A_i \times FAR \] \hspace{1cm} (3)

\[ HA_i = TFA_i \times HAR_j \] \hspace{1cm} (4)

\[ CA_i = TFA_i \times 0.3 \text{ or } 0.15 \] \hspace{1cm} (5)

where \( TFA_i \) is the gross floor area of a building; \( S A_i \) is the site area; \( FAR \) is the floor area ratio; \( j \) is the usage type of the building; \( HA_i \) is the heating area; \( HAR \) is the heating area ratio; and \( CA \) is the cooling area. The heating area ratio by the usage type of a building is shown in Table S2 in the “Supporting information”.

After finding the heating and cooling area, its connected heat load can be calculated through Eqs. (6) and (7), respectively. The connected heat load is the heat load needed for the facility of each user and a design standard for district cooling and heating pipeline network.

\[ HCHL = \sum_{i=1}^{n} \left( HA_i \times UHL_i \right) \] \hspace{1cm} (6)

\[ CCHL = \sum_{i=1}^{n} \left( CA_i \times UCL_i / CoP \right) \] \hspace{1cm} (7)

where \( HCHL \) is the heating connected heat load; \( UHL \) is the unit heat load; \( CCHL \) is the cooling connected heat load; \( n \) is the number of buildings; \( UCL \) is the unit cooling load; and \( CoP \) is the coefficient of performance. In the calculation of the cooling connected heat load, the coefficient of performance of hot water driven absorption chiller is 0.72, and one of double-lift absorption chiller is 0.64. The unit heating and cooling loads by the usage type of a building are shown in Tables S3 and S4 in the “Supporting information”.

The peak heat load indicates the maximum value among the heat loads fed from the heat source facilities upon satisfying the heat demand of the demand side. It is used as the data to decide the capacity of the equipment in heat supply facilities. This is estimated by multiplying the connected heat load in the demand side by the maximum load factor (Eq. (8)).

\[ PHL = \Sigma \left( (HCHL + CCHL) \times MLF \right) \] \hspace{1cm} (8)

where \( PHL \) is the peak heat load; and \( MLF \) is the maximum load factor. In this study, 55% was applied as the maximum load factor.

The heat demand quantity of the region can be obtained by considering the peak heat load and the heat use time.

2.3. Co-benefits analysis of industrial symbiosis

In this study, the reduction of fuel cost and \( \text{CO}_2 \) emission is considered as the economic and environmental benefit, respectively. The calculation method of \( \text{CO}_2 \) emission and fuel cost reduction are as follows. The estimated avoided amount of fossil fuel consumption or \( \text{CO}_2 \) emission for companies is shown in Eq. (9):

\[ EnvG_{ij} = F_{ij} \] \hspace{1cm} (9)

where \( EnvG_i \) is the avoided fossil fuel consumption or \( \text{CO}_2 \) emission for a company or sector \( i \); \( F_{ij} \) is the avoided fuel consumption due to the symbiotic activities; and \( j \) is the fuel type.

\[ F_{ij} = S_i \times H_{ij} \] \hspace{1cm} (10)

In Eq. (10), \( F_{ij} \) is the multiplication of the fuel substitution rate (\( S_i \)) and the quantity of reused/recycled energy or heat (\( H_{ij} \)). It is noted that there are some limitations to this calculation. This includes the exclusion of resource consumption and waste emission that occurs as tradeoff for the symbiosis, and incomplete data availability from company which means that only the first-proxy quantifications of fuel conservation and emissions reduction from the symbiosis is utilized.

After quantifying the flows and gaining the avoided fossil fuel consumption or \( \text{CO}_2 \) emission, the \( \text{CO}_2 \) emission reduction is calculated by applying the \( \text{CO}_2 \) emission coefficient by fuel types in Eq. (11):

\[ CR_{ij} = CEF_j \times EnvG_{ij} \times 44/12 \] \hspace{1cm} (11)

where \( CR_{ij} \) is the \( \text{CO}_2 \) emission reductions from the avoided fuel \( j \) in
company i and $CEF_j$ is the carbon emission factor of the fuel j.

The $CEF_j$ could be gained from the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). According to the 2006 IPCC guidelines (IPCC, 2006), the carbon emission factors of bunker C fuel oil (B-C oil) and liquefied natural gas (LNG) are 21.1 and 15.2 ton C/TJ, respectively.

The fuel cost reduction is calculated by applying the price by fuel types in Eq. (12):

$$FCR_{ij} = F_j \times EnvG_{ij}$$

(12)

where $FCR_{ij}$ is the fuel cost reduction from the avoided fuel $j$ in company $i$, $F_P$ is the price of the fuel $j$.

The $F_P$ could be gained from the Korea National Oil Corporation (KNOC) and KyungDong City Gas. According to the price information of B-C oil by the KNOC (“Oil information,” 2015), the B-C oil price in the oil selling agency is 634.2 KRW/liter as of April 2015. The gross caloric value of B-C oil is 41.6 MJ/liter (Enforcement Rule of the Energy Act, 2013). The price per MJ of B-C oil therefore is 15.2 KRW/MJ. According to the price information of LNG by the KyungDong City Gas (“City gas price information,” 2015), the LNG price for heating in the house is 19.7 KRW/MJ as of March 2015.

2.4. Data collection

Actual data were collected as much as possible. To estimate the potential heat sources, the data for annual fuels and electricity consumption of the energy-consuming companies in Ulsan as of 2013 were obtained from Ulsan metropolitan city. To estimate the potential heat sinks in industry, the data for the potential demand and the energy type of each company which wanted to introduce energy from outside was obtained from the manager interview of each company and the results of the survey questionnaire conducted by the KEMCO Busan/Ulsan branch office (A study on the expand utilization plan of surplus energy potential in Ulsan industrial complexes, 2014). To estimate the potential heat sinks in urban region, the data for the site area and the floor area ratio of the residential and non-residential buildings were obtained from the building ledger of the district offices for each building. The data for the heating area ratio, unit heat load, unit cooling load, coefficient of performance, and maximum load factor were obtained from the documentation guidelines for the proposal of integrated energy (The documentation guidelines for the proposal of integrated energy, 2012). To check the validity of the energy demand values in urban regions estimated by the heat load analysis procedure, the data for the real city gas consumption of some buildings were obtained from the report of KyungDong City Gas. The carbon emission factors of the B-C oil and LNG were obtained from the 2006 IPCC guidelines (IPCC, 2006), and the prices of the B-C oil and LNG were gained the KNOC (“Oil information,” 2015) and the KyungDong City Gas (“City gas price information,” 2015).

2.5. Scenario setting

Based on the above information of IS development in Ulsan, the features of companies and industries, as well as the heat sources and sinks analysis, four scenarios (Fig. 6) for I-US networks are designed considering step-wise expansion in future, including business of usual (BAU) scenario (Fig. 7). For BAU scenario, it is identified as the current energy IS network in Ulsan. The detail scenarios design are as follows:

(1) Scenario 1: expansion of current IS network: This scenario considers that potential heat sources produced from industries would be supplied and utilized to the 11 industries. In this condition, approximately 3146 TJ/yr of the potential heat sources are utilized. The supplied heat sources substitute the fossil fuel consumption. The companies located in the industrial complexes in Ulsan utilize Bunker-C (B-C) oil as its fuel fossil.

(2) Scenario 2: establishment of an US network: This scenario considers that potential heat sources that would be utilized and supplied in the Nam-Gu1 area, where, has a high potential to establish an US between industrial complex and urban region due to being close to the Ulsan-Mipo national industrial complex. Thus, Nam-Gu1 is considered first as the area for the US network. About 3450 TJ/yr of the potential heat sources are supplied to the Nam-Gu1 area among the urban regions. The supplied heat sources serve as a substitute to the liquefied natural gas (LNG) consumption because LNG is normally utilized as a heating source for the urban region in Korea.

(3) Scenario 3: expansion of designed US network as Scenario 2: This scenario considers the potential heat sources that would be supplied to the Nam-Gu2 area, i.e. the potential heat sink of Nam-Gu2 is considered for expanding the US network. About 2294 TJ/yr of the potential heat sources is supplied to the Nam-Gu2 area, and the supplied heat sources serves as a substitute to the LNG consumption.

(4) Scenario 4: expansion of US network to other regions: This scenario considers the potential heat sources that would be supplied to the other regions, i.e. the potential heat sinks of the other regions are considered for expanding the US network. Considering the potential heat sinks of the other 4 regions, about 9680 TJ/yr of the potential heat sources is supplied to the regions that serve as a substitute to the LNG consumption.

3. Results and discussions

3.1. Potential heat sources and sinks in industrial sector

3.1.1. Heat sources

There are 183 high energy-consuming companies in Ulsan as of 2013. Annual fuels and electricity consumption of these companies are 11.78 MTOE, and 5.92 MTOE (25.75 TWh). Annual total energy consumption is therefore 17.70 MTOE as shown in Table 2. Considering the fuel consumption and waste heat inventory profile of the different production system, the potential energy resources produced from industries were conservatively estimated at about 0.59 MTOE/yr of high grade waste heat and 0.59 MTOE/yr of low grade waste heat. Thus, the total potential of heat sources is 1.18 MTOE/yr (10% of total energy consumption) and the joule value of about 49.32 TJ/yr.

Upon review the energy audit reports, several companies have tried
to recover high-grade waste heat through mechanical vapor recompression (MVR) installation, process improvement, energy outsourcing, and other ways. However, there is still a lot of energy that are not used, but only emitted to the air in Ulsan. In the case of company "A", it could reduce the steam consumption by improving the structure and operation method of purified terephthalic acid (PTA) dryers, and could recover the heat from the exhaust gases of synthetic heat transfer fluid boilers. Company "B" could also reduce the steam consumption by improving the structure of crude terephthalic acid (CTA) and PTA dryers, and by changing the distillation columns to normal butyraldehyde (NBA) extraction process. Therefore, the reduced steam and recovered heat by improving the processes could be fully utilized as the heat source for symbiosis.

And according to the 4th regional (new and renewable) energy plan of Ulsan (The 4th regional (new and renewable) energy plan, 2013), the available waste heat sources produced from the industrial sector in Ulsan was $810.5 \times 10^3$ TOE/yr as of 2010 shown in Table S5. This report assumes 8% energy recovery rate and 75% efficiency of its recovery system. The total potential of industrial waste heat was estimated to be $960 \times 10^3$ TOE/yr with $150 \times 10^3$ TOE/yr are already used by industrial symbiosis networks in 2013. However, the industrial networks increase as years passed, the used industrial symbiosis network is $180 \times 10^3$ TOE/yr at the end of 2016, a 16.7% increase after 3 years. Though energy recovery rate were assumed to be 6% of the total energy consumption in the industrial sector, low-grade waste heat was not considered in the 4th regional (new and renewable) energy plan (2013), and an energy recovery potential of $1180 \times 10^3$ TOE/yr of this research is higher than $960 \times 10^3$ TOE/yr of the 4th regional energy plan. However, the high-grade heat value of $590 \times 10^3$ TOE/yr estimated by the energy consumption of the energy-consuming companies is lower than the suggested value in the 4th regional (new and renewable) energy plan.

3.1.2. Heat sinks

According to the data for survey questionnaires and manager interview, some companies still want to introduce energy from outside companies. Table 3 lists the energy demand status with available information for each company. The potential energy demands of 11 companies are about 127–162 ton/hr of steam or hot water. In order to match the figures of potential supply and demand, it is necessary to convert the unit of potential energy demand from mass unit (ton/hr) to heat value unit (TJ/yr). This study assumes that the needed caloric value of the steam of the 11 companies is 650 kcal/kg. The total caloric value of the potential energy demand is therefore ranging from 2765 to 3527 TJ/yr. The annual operation time is assumed to be 8000 h and the total calorific value used is averaged at 3146 TJ/yr.

3.2. Heat sinks in urban regions

3.2.1. Validation of the energy demand

In order to check the validity of the energy demand values calculated by the heat load analysis procedure, the calculated figures are compared with the real energy consumption figures (city gas consumption) by randomly selecting 24 apartment building complexes. The calculated figures were similar to the real figures shown in Fig. 8. It is appropriate to apply the heat load analysis for energy demand scenario design in urban area.

3.2.2. Heat sinks in urban regions

Table 4 lists the potential energy demand calculated by the heat load analysis procedure for four administrative districts in Ulsan. As mentioned in Section 3.2, the apartment building complexes with more than 300 households are involved in the residential buildings, while hypermarkets, department stores, office buildings, and hospitals are...
included in the non-residential buildings. Nam-Gu is divided into 2 areas (Nam-Gu1 and Nam-Gu2) in this study. Nam-Gu1 is a partial area of Nam-Gu that is close to the Ulsan-Mipo national industrial complex. Therefore, Nam-Gu1 has a high possibility to establish a low heat energy IS network between industrial complex and urban region.

There are 11,381 households (apartment house) and 14 non-residential buildings in the area of Nam-Gu1. The selected apartment houses are close to the Ulsan-Mipo national industrial complex, while the selected non-residential buildings include department stores, hypermarkets, hospitals, and large sized office buildings. The heating and cooling peak heat loads around Nam-Gu1 are 59.0 and 44.0 Gcal/hr, respectively. Nam-Gu2 is slightly farther away than Nam-Gu1 in terms of their distance to the industrial complex. Nam-Gu2 area has 13,066 households (apartment house) and 8 non-residential buildings (hospitals, hypermarkets, broadcasting station and district office). The heating and cooling peak heat loads of Nam-Gu2 are 56.4 and 12.1 Gcal/hr, respectively. Consequently, the heating and cooling peak heat loads of the whole Nam-Gu are 115.4 and 56.1 Gcal/hr, respectively.

The Beomseo region includes partial areas of three administrative districts (Nam-Gu, Jung-Gu, and Ulju-Gun) due to its overlapping area among the three districts in this region. This study thus considers these areas as one separate region. Beomseo region is 15 km away from the industrial complex. The cooling heat loads in this region is zero due to having no presence of non-residential building. The heating peak heat load is estimated to be 72.1 Gcal/hr. The Buk-Gu region is a residential area in which the new housing estates are concentrated. It is also 15 km away from the industrial complex. The heating peak heat load is 75.2 Gcal/hr. The Onsan region belongs to Ulju-Gun and is close to the Onsan national industrial complex. There are small-scale apartment houses and dormitories of companies located in Onsan, and its heating peak heat load is 10.1 Gcal/hr. Moreover, the heating peak heat loads of Dong-Gu and Jung-Gu region are 50.5 and 81.1 Gcal/hr, respectively. Hence, the total heating and cooling peak heat load is 404.4 and 56.1 Gcal/hr, respectively, converting these figures into joule unit would result to 13,545 and 1879 TJ/yr, respectively.

The summary for the estimated potential heat sources and sinks in Ulsan is shown in Table 5. Results highlighted that in principle, the potential heat sources are well over the potential heat sinks. The potential heat sources specifically generated from the industries can provide about 24,659 TJ/yr for both the high and low grade waste heat, respectively, while the potential heat sinks of the high and low grade heat were 3146 TJ/yr and 13,545 TJ/yr, respectively. Moreover, an observed 1879 TJ/yr for cooling was much less than the supply potential even after the consideration of future industrial projections.

<table>
<thead>
<tr>
<th>Regions</th>
<th>No. of households</th>
<th>Connected heat load (Gcal/hr)</th>
<th>Peak heat load (Gcal/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>Cooling</td>
<td>Heating</td>
<td>Cooling</td>
</tr>
<tr>
<td>Nam-Gu1 (14 buildings)</td>
<td>11,381</td>
<td>107.2</td>
<td>79.9</td>
</tr>
<tr>
<td>Nam-Gu2 (8 buildings)</td>
<td>13,066</td>
<td>102.5</td>
<td>22.0</td>
</tr>
<tr>
<td>Total of Nam-Gu</td>
<td>24,447 (22 buildings)</td>
<td>209.7</td>
<td>101.9</td>
</tr>
<tr>
<td>Jung-Gu (7 buildings)</td>
<td>22,605</td>
<td>147.5</td>
<td>81.1</td>
</tr>
<tr>
<td>Beomseo</td>
<td>23,155</td>
<td>131.1</td>
<td>72.1</td>
</tr>
<tr>
<td>Buk-Gu</td>
<td>22,778</td>
<td>136.8</td>
<td>75.2</td>
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<tr>
<td>Dong-Gu</td>
<td>18,620</td>
<td>91.8</td>
<td>50.5</td>
</tr>
<tr>
<td>Onsan (7 buildings)</td>
<td>2932</td>
<td>18.4</td>
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<tr>
<td>Total</td>
<td>114,537 (29 buildings)</td>
<td>735.3</td>
<td>101.9</td>
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Table 5 Summary of potential heat sources and sinks in Ulsan.

3.3. Economic and environmental effects of the four scenarios

The reduction of CO2 emission and fuel cost can be calculated by considering the aforementioned scenarios for the potential I-US networks. These results are presented in Table 6 and Fig. 9. In the scenario for the expanded IS network, by substituting the B-C oil consumption through the utilization of the potential heat sources, the CO2 emission and fuel cost could be reduced to 0.24 Mton/yr and 48 million US Dollar/yr, respectively.

By substituting LNG consumption through the utilization of the potential industrial waste heat sources, the scenario for the US network could reduce the CO2 emission and fuel cost by 0.19 Mton/year and 68.1 million US Dollar/yr, respectively. The scenario 1 for the expanded US network results in the reduction of CO2 emission and fuel cost by 0.54 Mton/yr and 191.1 million US Dollar/yr, respectively. Furthermore, in the scenario 2 for the expanded US network, it will further contribute to the reduction of the CO2 emission and fuel cost by 0.54 Mton/yr and 191.1 million US Dollar/yr, respectively. Consequently, the scenarios for whole US networks could reduce the CO2 emissions by 0.87 Mton/yr, and the fuel cost could be reduced by 304.5 million US Dollar/yr.

Based on the results, if all the potential I-US networks were established and implemented, the total CO2 emission reduction is 1.11 Mton/yr and the total fuel cost reduction is 352.5 million US Dollar/yr. This reduction of CO2 emission is approximately 2% of the total CO2 emissions in Ulsan (about 54.27 Mton CO2 eq./yr as of 2016). High-grade waste heat sources could be utilized in other industries, and even the low-grade waste heat sources with low operating conditions (low temperature and pressure) could be utilized as the heating source for urban regions. Therefore, CO2 emission and fuel cost could be effectively reduced through I-US networks. The analysis verifies that the potential I-US networks could reduce the extra CO2 emissions by 1.11 Mton/yr. It can also strongly support sustainable development and local regeneration in a more environmentally friendly perspective.
3.4. Implementation strategy

The energy used in the manufacturing processes is not fully optimized; some are discharged to the environment which is lost as waste heat. Among the potential heat sources, some heat sources with high profitability for symbiosis were already utilized for existing IS networks (7634 TJ/yr). This means that high profitable IS network (payback period less than 3 years) could be easily implemented by stakeholder negotiation as shown in Table 1. Table 7 summarize the result of the economic evaluation for scenarios 2, 3 and 4. The final investment costs and payback periods were estimated to be 45.0, 63.4 and 100.5 billion KRW and 9.7, 7.8 and 6.0, respectively. This I-US network project cannot be implemented by a company to company IS project which normally has a payback period of less than 3 years.

Thus, low profitable I-US networks which needs huge investment, have long payback periods and involve diverse stakeholders that must be designed by specific implementation strategy. In order to implement I-US networks, it must be noted that the industrial park has a very important urban infrastructure to maintain the economic development and job creation of the region. There is a widespread recognition that the governments cannot afford to bridge these growing infrastructure gaps through tax revenues and aid alone, and that greater private investment in infrastructure is needed (OECD, 2015).

As the I-US network has a slightly longer payback periods than the normal company to company IS networks (less than 3 years payback period) and much shorter than the normal infrastructure investment (around 20 years payback period), the public private partnership (PPP) business model can be developed to attract the public sector (local government or public organization) investment such as #13 in Table 1. This project attracted 28, 6.6 and 32.1 million US$ from SK Chemical, SK energy and Korea Industrial Complex Corporation (KICOX) affiliated to the Ministry of Trade, Industry and Energy (MOTIE), Korea to construct a steam pipeline of 6.2 km and diameter of 50 cm to transport 100 ton steam/hr. In the eco-town project of Japan, government gives subsidies to construct eco-town facilities such as incinerator. The EIP program in Korea provide only the IS feasibility study and business model including the investment, and the benefit sharing of the I-US must be developed by the feasibility study. However, a small subsidy for I-US infrastructure would attract more private investment in the I-US project like eco-town program in Japan.

The energy related policy fund such as the energy service companies (ESCO) fund of Korea can be a good consideration to provide loans for the I-US projects to help facilitate the installation of waste heat recovery facilities by providing equipment installation and construction of piping lines costings which needs huge investment to startup the I-US energy networks. Though the low grade energy network reduces carbon emission, the carbon emission reduction certification is not issued. To increase the business profitability of the I-US networks, institutionalizing the carbon emission reduction is highly recommended. If the carbon emission reduction is provided in our scenarios, the payback periods are reduced by 0.9 – 1.3 year. In developing a I-US business model, the perspective of cooperation, equivalent responsibility and benefit sharing of supplier and demander, principle of 50% investment and 50% benefit sharing opportunity must be guaranteed (Kim et al., 2017). The GHG benefits from the I-US networks developed through the collaborations of heat sources and heat sinks can be apportioned through a 50/50 allocation method (Kim et al., 2017). However, this study recommends a more negotiable, practical and reasonable implementation approach among the stakeholders based on the investment and contribution of stakeholders towards the I-US implementation.

![Fig. 9. (a) CO₂ emission reduction and (b) fuel cost reduction by the scenarios for the potential I-US networks in Ulsan.](image-url)
4. Conclusions

This study investigates the potential I-US using industrial waste heat sources and evaluates the potential economic and environmental benefits within the current energy status in Ulsan. The potential waste heat sources in industrial parks was estimated by multiplying the total energy consumption of a high energy consuming company (more than 2000 TOE in a year) and the production rate of its waste heat. This study conservatively regards the production rate of waste heat as 10%, 5% high grade and 5% low grade, considering the waste heat recovery potential. The total potential waste heat sources in industrial park estimated by the above-mentioned method are 49,321 TJ/yr. The potential heat sink sources for the expanded IS network estimated by the above-mentioned method are waste heat as 10%, 5% high grade and 5% low grade, considering the company (more than 2000 TOE in a year) and the production rate of its sources and evaluates the potential economic and environmental benefits.

Table 7
Economic evaluation for scenarios 2–4.

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<td>Value</td>
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<td>Profit</td>
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Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2017.09.027.

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