FEASIBILITY ASSESSMENT OF ENERGY TRANSITION FROM A FOSSIL FUEL TO LOCAL RESOURCE BASED HEATING SYSTEM USING THERMOECONOMIC ANALYSIS

Ivar Baldvinsson, Tohoku University, Phone: +81-22-795-6987, email: ivar@most.tohoku.ac.jp
Takaaki Furubayashi, Tohoku University, Phone: +81-22-795-6987, email: furubayashi@m.tohoku.ac.jp
Toshihiko Nakata, Tohoku Universtiy, Phone: +81-22-795-7004, email: nakata@m.tohoku.ac.jp

Overview

Space heating and domestic hot water account for about 50% of residential and commercial sector energy consumption in relatively cold climates. This energy service demand is generally met by fossil fuels causing considerable amount of GHG emissions. In Japan the supply system is mainly constructed of small scale, distributed, building based conversion units being supplied by imported fossil fuels or electricity. In addition to being carbon intensive and almost completely dependent on imported fossil fuel, space heating in residential sector of Japan has been estimated to have energy and exergy efficiency of 99.8% and 4.6%. The low exergy efficiency indicates bad utilization of the available energy content of the supply fuel because of a mismatch between quality levels of the supply fuels and energy service demand. Fuel transition or restructuring of the heat supply system matching the quality level of the energy demand while fulfilling acceptable levels of availability, affordability and environmental impact is therefore of great benefit. District heating system is a flexible heat supply system that can integrate various local heat resources and has proven to supply heat in an effective and cost competitive way.

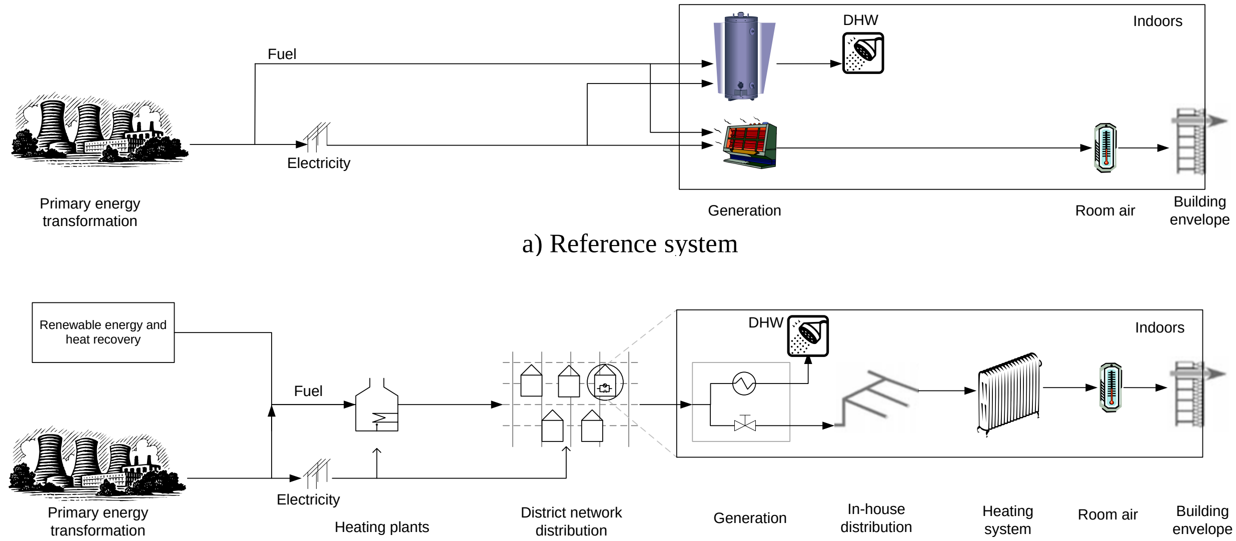
The purpose of this study is to assess the feasibility of a district heating system integrating local, low carbon energy sources, providing space heating and hot water on a small-city scale as a comparison to conventional fossil fuel based heating system. Study area is Hirosaki city located in north of Japan with relatively high fossil fuel prices and high heat loads. An energy analysis of the existing system is conducted, disaggregating the consumption by type of fuel and type of energy service demand. The district heating system is designed in order to match peak load. Steady state thermoeconomic analysis considering peak load conditions is conducted for assessing and comparing the two systems. Performance and exergoeconomic parameters are used to evaluate and compare the systems. Available feasible resources in Hirosaki considered for the district heating system are waste wood, municipal solid waste incineration plant waste heat, sewage sludge and geothermal energy. Together they are able to provide about 17% of the peak load. The insufficiencies of local resources are assumed being supplied by natural gas boiler. Results indicate a considerable reduction in CO_2 emissions and the thermoeconomic analysis indicates that low fuel cost and less exergy destruction compensate for the high capital investment cost required for transition to district heating system. Energy efficiency is higher of the reference system and exergy efficiency about the same for both systems at peak load.

Methods

Thermoeconomic analysis is used for assessing and comparing an existing heat supply system of the study area (reference system) and district heating system integrating local resources (alternative system). Thermoeconomic analysis is an effective tool for providing detailed evaluation and comparison of different energy sources and technologies. It provides numerical analysis quantifying the exergy and accounts for energy degradation and its cost in the economical analysis.

A demand analysis of the reference system is conducted, disaggregating the demand by type, space heating and hot water, and type of supply system and the peak load is calculated. The alternative system is designed according to the peak heat and hot water load of the study area. Available local resources and their energy potential are identified. Heat plants are sized according to heat source potential and heat load as well as size of distribution network, circulation pump and heat emission system are estimated.

The thermoeconomic analysis consists of four steps: exergy analysis, economy analysis, exergy costing and evaluation. The Exergy analysis used (developed by Dr. Dietrich Schmidt) considers the whole energy supply chain from sink to source, carried out at a defined subsystem level. The supply chain and composing subsystems of the reference system and district heating system are presented in Figure 1. The exergy analysis is based on exergy balance at subsystem level. In the economical analysis the total annualized cost of components of the supply chain are estimated. Exergy costing involves linking cost values with exergy streams through cost accounting. A general simplified equations for the exergy balance, exergy costing and relation equation are shown in (1), (2) and (3) respectively. $\dot{E}x_f$, $\dot{E}x_p$ and $\dot{E}x_D$ are the exergy rate of the fuel streams, product streams and destruction of a subsystem respectively in [MW]. $\dot{C}_f$ and $\dot{C}_p$ are the cost streams accordingly and $\dot{Z}$ is the annualized total cost stream of a component in [$/sec]. c_i is a average cost per unit of exergy of stream i in [$/GJ].



a) Reference system

b) District heating system

Figure 1 The supply chain divided into subsystems for studied heating systems.

$$\sum_f \dot{E}x_f = \sum_p \dot{E}x_p + \dot{E}x_D \quad (1)$$

$$\sum_f \dot{C}_f + \dot{Z} = \sum_p \dot{C}_p \quad (2)$$

$$\dot{C}_i = c_i \dot{E}x_i \quad (3)$$

Results

The two systems are evaluated using several performance and thermoeconomical factors. The energy and exergy efficiency of the reference system are 0.75 and 0.088 respectively and of the district heating system 0.64 and 0.086. The 10% indifference in energy efficiency indicates that the district heating system is more suitable supplying low quality energy demand as the exergy efficiency is about the same. The reference system's power requirement is 18.4 MW but 4.8 MW in terms of the district heating system. By transition to a district heating system, tremendous CO_2 reduction can be obtained, from annual 572,000 t-CO_2 of the reference system to 251,000 t-CO_2. The output of the thermoeconomic analysis of each of the systems' subsystems is presented. The exergy unitary cost formation shows how space heating and domestic hot water generation cost should be divided between them. For the reference system the average unitary exergy cost for space heating and domestic hot water is 278 $/GJ and 244 $/GJ respectively and for the district heating system it is 295 $/GJ and 30 $/GJ respectively. The low domestic hot water unitary exergy cost of the district heating system is due to synergy effect of the distribution network and low capital cost of plate heat exchangers. The high unitary exergy cost of the reference system is because of high heating radiator capital cost and exergy losses in the in-house distribution system and room air. The reference system is composed of independent heating systems having no synergy effect, thus both the domestic hot water and space heat unitary exergy costs are similar and have high fuel cost entering the "Generation" subsystem where majority of the exergy destruction of the reference system occurs. This also occurs higher cost of exergy destruction in the reference system, 24.8 $/sec compared to 20.4 $/sec as the dominating share of exergy destruction of the district heating system occurs in the "Heating plants" at lower fuel cost. The R_{ex} factor, ratio of exergy destruction to capital cost, is 23.3 W/$ and 2.6 W/$ of the reference and district heating system respectively. The total exergy destruction of the systems is similar, indicating considerably higher capital investment cost required of the district heating system.

Conclusions

Thermoeconomic analysis indicates that transition to a district heating system from small scale distributed fossil fuel based conversion unit system has good potential as low fuel cost and less degradation of energy compensate high investment cost requirement. Although having lower energy efficiency the local heat sources are more suitable providing low quality energy demand due to lower quality factors. The local resources considered in this study are able to supply about 17% of the peak heat load at little higher space heating unitary exergy cost but at much lower domestic hot water unitary exergy cost while emitting more than 50% less of CO_2. The district heating system studied has considerable potential for improving the energy efficiency and exergy efficiency e.g. by using co-generation units instead of heat only boilers, adjust the district heating supply and return temperatures or by use the source in cascade way. At lower loads the results become more favourable to the district heating system due to higher share of local resources at the cost of natural gas improving exergy efficiency and reducing fuel cost.