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A Strategic Study of Energy Efficient and Hybrid Energy System Options for a Multi-family Building in Korea

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Abstract

This study is to identify performance of energy efficiency measures and to match low-carbon and renewable energy (RE) systems supplies to demands in the context of multi-family residential buildings in Korea. An approach to the evaluation of the hybrid energy systems was investigated, including consideration of heat and power demand profiles, energy system combinations, building design options and strategies for matching supply to demand. The approach is encapsulated within an integrated software environment. Building energy simulation technology was exploited to make virtual energy use data. Low-carbon and RE system modelling techniques were used to predict energy supply profiles. A series of demand/supply matching-based analyses were made to identify the effect of energy efficient demand measures (e.g. roof-top gardens, innovative under-floor heating system) and evaluate the capacity utilisation factor from the hybrid energy systems. On the basis of performance information obtained at the conceptual design stage, the design team can pinpoint the most energy efficient demand/supply combination, and consequently, maximise the impact of hybrid energy systems adoption.

Keywords: Renewable energy, multi-family building, demand/supply matching, decision support system

1. Introduction

The requirement for environment friendly and energy efficient domestic buildings is growing in Korea. A demonstration building of a sustainable domestic building project, so-called PLUS 50, is planned to be constructed in an urban area of Seoul in Korea. The purpose of the PLUS 50 project is to develop technologies of design, construction structure, materials and energy systems for residential buildings which prolong building life by 50% and reduce environmental impact by 50%. In terms of ecological and environment friendly design aspects, a number of individual technologies are considered such as the panel-module type Ondol system (an innovative under-floor heating system with pre-fabricated panel structure, high radiation emissivity surface and low supply water temperature), green roof (roof consisting of soil, plant, membranes, and drainage barriers to reduce heating/cooling load, storm-water runoff and the urban heat island) and low carbon and renewable energy systems as illustrated in Figure1.

To successfully integrate low-carbon and renewable energy (RE) systems within a building, appropriate technology types and capacities must be identified and integrated. In a previous study, a new approach to deal with interactive effects of the RE systems and building was suggested to support the design team in the early design stage [1]. The study focused on the feasibility test of building design options (e.g. roof shape, orientation etc) and RE systems including PV, solar collectors and heat pump, and concentrated on the matching of the outputs from new and RE systems to demand.

In addition to RE systems, μCHP is a useful auxiliary device to compensate for the gap between renewable energy supply and residential energy demand. Because it can generate electricity and heat simultaneously, it is important to operate the system to most effectively match the year-round heating and electricity loads. Due to the varying demands, it is necessary to investigate strategies for simultaneously meeting heating and electricity loads within the PLUS 50 building.

To this end, it is necessary to evaluate key technology elements in an integrated manner and establish appropriate strategies for demand/supply matching. The aim of this study is, therefore, to identify the effect of energy efficient demand measures (e.g. roof-top gardens, innovative under-floor heating system) and maximise the capacity utilisation factor from the hybrid energy (HE) systems.

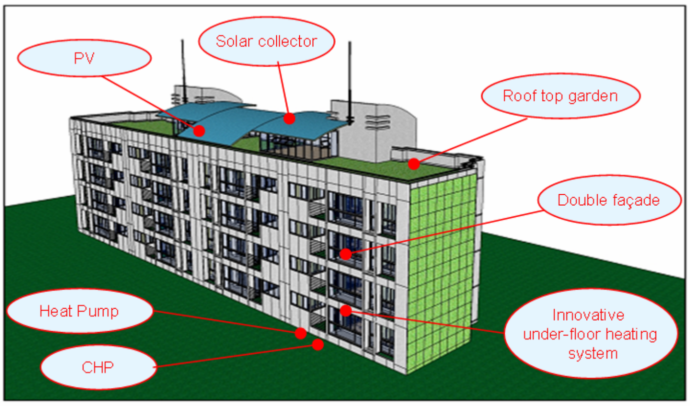

Fig. 1: PLUS 50 building design concept.

2. Software framework

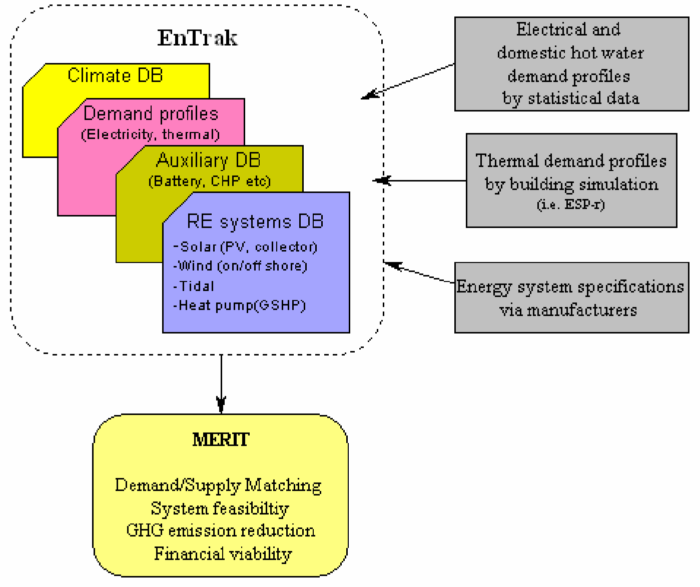

Fig. 2: Software framework for demand/supply performance evaluation.

As depicted in Figure 2, the software system used for the study consists of an integrated building energy simulation program (*ESP-r* [2]), a new and renewable energy modelling and matching tool (*Merit* [3, 4]), and an information management (*EnTrak* [5]). The *Merit* system is a quantitative evaluation tool that allows the user to determine the match between supply and demand in order to make informed decisions about the suitability of certain supply mixes for particular applications. In *Merit,* algorithms that model RE and low-carbon energy systems (photovoltaic components, solar collectors, wind turbines, CHP, heat pump, fuel cells *etc*.) are established to simulate power production based on manufacturers' specifications, locational parameters and weather data. *EnTrak*, an energy and environment information management tool, is used to store climate databases and the demand and supply profiles for use with *Merit*'s profile matching feature. *ESP-r* is used to model the proposed design in order to generate virtual demand profiles corresponding to the building's environmental control systems.

3. Simulation model and demand/supply profiles

3.1 Thermal model and design options

The PLUS 50 building design comprises 20 households with 4 apartments on each of 5 storeys. The thermal model of the PLUS 50 building was generated by ESP-r including the Ondol under-floor heating system and green roof. To implement the thermal performance and demand/supply matching studies, 4 variations of the PLUS 50 model were defined according to the types of Ondol system (i.e. conventional and panel-module types) and the roof construction variants (i.e. conventional roof and green roof) as described in Table 1. The conventional roof has a U-value of 0.46 W/m^{2}K. The green roof has a 120 mm soil over insulation and concrete, and has an improved U-value of 0.35 W/m^{2}K. The main façade of the model is assumed to face South for all cases . The hourly climate data of Seoul (37.34˚N, 126.58˚E) was used. In this climate dataset, the heating load comprises the majority of the total load. The analysis therefore focused on the heating season.

Table 1: Model cases.

Case	Design options
1	Conventional Ondol + conventional roof
2	Panel module Ondol + conventional roof
3	Conventional Ondol + green roof
4	Panel module Ondol + green roof

3.2 Electricity and domestic hot water demand profiles

Electricity and domestic hot water use were collected from literature reviews [6]. Typical daily profiles of home appliances were adjusted to the PLUS 50 building scale (i.e. 20 households) and extended to annual profiles using *Merit*'s profile designer.

3.3 Supply-side options

The heat pump, solar collector and µCHP systems were adopted for the heating energy supply system. The capacity and COP of the heat pump system are 10 kW and 3.8 respectively for heating. Assuming that the heat pump is operated in on/off mode, the supply from the system is essentially constant because it does not depend on climate but on ground temperature at a 70-100m depth, which is essentially steady at around 13ºC in winter and 15ºC in summer. Two types of CHP models were selected for the analysis. The first was a µCHP system from the Capstone Company (50 kW capacity) [7]. The second was a smaller micro turbine (30 kW) selected from the publication of the Energy Nexus group [8]. For the electricity supply system, a 80-Watt multi-crystalline photovoltaic module [9] was used within the matching analysis.

3.4 µCHP control model

Two different operational modes were defined for the control model: electricity-led and heat-led, with the heat-to-power ratio and partial load performance taken into account in both cases. The model is based on manufacturers' performance data. The performance of a µCHP system is dependent on the load it is expected to follow. Other factors such as the ambient temperature and altitude are also considered in the model as implemented. From the fuel consumption curve and heat-to-power ratio curve, the performance characteristics of the system are calculated. These include metrics such as fuel consumption, by-product heat/electricity energy production, overall efficiency and greenhouse gas emissions.

4. Analysis

4.1 Demand/supply performance with heating-led CHP control

The hybrid energy system consisting of a heat pump and a μCHP unit was examined for heating demand/supply matching. It was assumed that the heat pump covers the base load and the μCHP compensates for any supply deficit by following the thermal load profile with partial load control activated. Table 2 illustrates the key criteria of the demand/supply matching. The building models with the panel module Ondol system (i.e. case 2, case 4) have better matches and consequently low deficit/surplus supplies, compared to the conventional Ondol system (i.e. case1, case 3). The peak heating load of the conventional Ondol system is higher than that of the panel module Ondol system. This implies that the conventional Ondol systems require a larger capacity supply-side system. Generally, the panel module Ondol system gives rise to a relatively low energy demand and provides a stable thermal environment.

While the thermal effect of the green roof gives rise to a 7-8 % reduction in thermal energy demand, the green roof-installed building models (i.e. case 3 and case 4) lead to better performance of the supply-side system. Case 4 (green roof plus panel-module Ondol) is the best performer in terms of thermal characteristics, demand/supply matching rate (96.45%), μCHP fuel consumption and μCHP capacity and has the lowest deficit (330 kWh). This deficit could be resolved by adopting additional demand side measures (e.g. additional insulation, improved glazing, more efficient ventilation control), which would also reduce peak demand and allow a smaller μCHP capacity. Note that the metric used for matching of the supply and demand profiles, the match rate, is defined as (1 - Inequality) x 100. Here, Inequality is a statistical indicator describing the quantitative fit in a time-series due to three sources: unequal tendency, unequal variation and imperfect co-variation [4]. Residual values indicate a deficit or surplus of supply energy (negative values imply a surplus).

Table 2: Demand/supply matching - heat pump + μCHP (heating-led control mode in January).

Combinations			Demand [MWh]	RE Supply [MWh]	Aux Supply [MWh]	Match Rate [%]	Residual [MWh]	Fuel Natural Gas [m^3]
Demand	RE	CHP						
Case 1 +DHW	Heat Pump	Nexus	27.53	7.89	18.59	92.38	1.053	5332.4
Case 2 +DHW			27.22	7.89	18.95	96.37	0.376	5451.4
Case 3 +DHW			26.34	7.89	17.50	91.75	0.952	4897.0
Case 4 +DHW			26.40	7.89	18.17	96.45	0.330	5160.2
Case 1 +DHW	Heat pump	Capstone	27.53	7.89	19.66	98.02	-0.009	6340.38
Case 2 +DHW			27.22	7.89	19.38	99.36	-0.046	6593.42
Case 3 +DHW			26.34	7.89	18.48	98.04	-0.028	5878.32
Case 4 +DHW			26.40	7.89	18.57	99.23	-0.057	6184.54

4.2 Demand/Supply performance with electricity-led μCHP control

An electricity demand/supply matching analysis was carried out with electricity-led μCHP control. Two roof-mounted PV systems were defined:

- PV_400_flat: 400 m^2 (whole roof area of PLUS 50 roof), flat type roof (tilt 0°)
- PV_200_flat: 200 m^2 (half roof area of PLUS 50), flat type roof (tilt 0°)

Compared to the heating-led control mode, the matching rates are relatively lower (Nexus 87%, Capstone 90%), and high residuals imply that supply profiles do not meet demand profile well. In addition, gas consumption is 160-180% higher than that of heating-led control. Although the gas consumption is higher in electricity-led control mode, by-product heat supply can be used to meet heating demand and vice versa. Therefore, it is also important to analyse the contribution of the by-product energy as µCHP generates heat and power simultaneously.

Table 3: Demand/supply matching for PV + µCHP (electricity-led control in January).

Combinations			Demand [MWh]	RE Supply [MWh]	CHP [MWh] (avg. efficiency)	Match Rate [%]	Residual [MWh]	Fuel Consumption (NG) [m^3]
Demand	RE	CHP						
Total electricity	pv_400_flat	Capstone	17.57	2.91	18.06 (77.43%)	90.51	-3.40	9917.76
	pv_400_flat	Nexus	17.57	2.91	14.21 (63%)	86.73	0.45	8413.52
	pv_200_flat	Capstone	17.57	1.46	19.29 (77.92%)	90.90	-3.17	10721.72
	pv_200_flat	Nexus	17.57	1.46	15.44 (63.45%)	87.07	0.68	9158.06

4.3 Effect of µCHP control modes and by-product supply

Table 4 presents a comparison of the effect of µCHP control on demand/supply matching. Generally gas consumption is larger with electricity-led control. The µCHP average running efficiency is also higher with electricity-led control. The matching rates are lower and give rise to a surplus which is partly associated with the renewable energy system (i.e. PV). Although the Capstone system has the better match, the Nexus µCHP could cover the demand if demand side measures are reinforced to reduce the peak demand. The electricity-led control mode produces a surplus heating supply and requires larger capacity of µCHP to meet demand without deficit.

When it comes to the effect of by-product supply, the by-product supply profiles of the Capstone and Nexus µCHP systems are similar as they are generated on the basis of the same demand. The matching rates range around 68% for by-product heating supply, with a surplus of 16 MWh. To improve the matching rate and utilise the surplus heating supply, additional systems such as heating storage may be required. On the other hand, using the electricity by-product from µCHP heating-led operation, results that the electrical match rate is lower (43-52%) with a supply deficit of 9.5 -12.4 MWh. Figure 3 shows a graphical view of demand and by-product electricity from the heating-led µCHP supply.

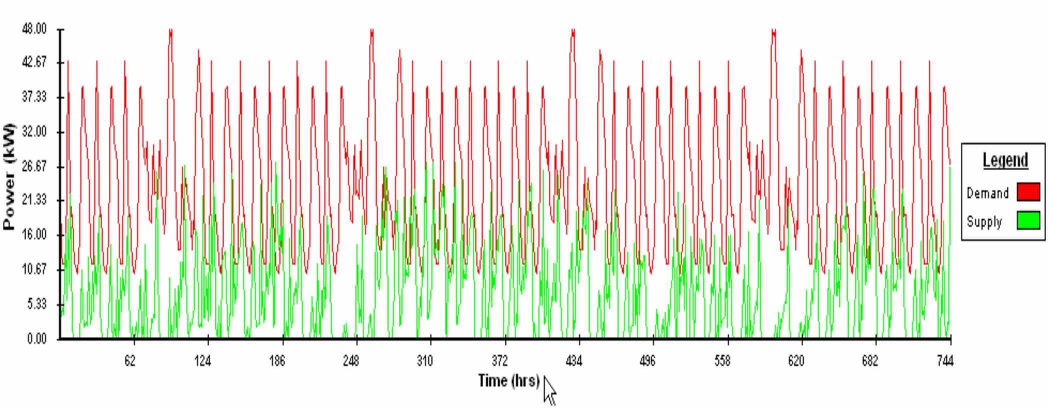

Figure 3: Matching electricity demand/supply with µCHP by-product supply..

In summary, the electricity-led control leads to over-capacity and additional systems while it satisfactorily generates supply to demand in both electricity and heating. On the contrary, when heat pump and µCHP are operated to tackle the heating demand, half of the electricity demand can be covered as well while the heating supply can meet the demand in good matching condition. In terms of installed capacity, gas consumption, match rate and by-product effect, consequently, heating-led control is the recommended approach.

Table 4: Comparison of the effect of μCHP control mode (period - January).

Control mode	Heating-led*		Electrical-led **	
	Nexus	Capstone	Nexus	Capstone
Gas consumption [m^3]	5160.24	6762.81	9158.06	10721.72
Match rate [%]	96.45	99.23	87.07	90.90
Residual [MWh]	0.330	-0.057	0.68	-3.17
Average Efficiency [%]	35	43	63	77
Matching with By-product	Match rate: 49.56 % Deficit supply: 10.90 MWh		Match rate: 68.42 % Surplus supply: 15.95 MWh	

*Demand: Case 4 + DHW, Supply: heat pump + μCHP, ** Demand: electricity, Supply: PV_200_flat + μCHP

5. Conclusion

In this study, a detailed approach to the evaluation of integrated HE systems was established, including consideration of heat and power demand profiles, energy system combinations, building design options and strategies for matching supply to demand. The approach is encapsulated within an integrated software environment. The important point in the approach is that the building and RE systems are dealt with in an integrated manner so that the essential interactions are fully considered.

A series of demand/supply matching-based analyses were made to identify the effect of energy efficient demand measures (e.g. roof-top garden, innovative under-floor heating system) and evaluate the capacity utilisation factor from the HE systems. On the basis of performance information obtained at the conceptual design stage, the design team can pinpoint energy efficient demand/supply combinations, and consequently, maximise the impact of hybrid energy systems adoption.

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