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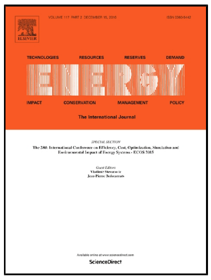

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- STG should be designed to store energy in the most efficient way at the most effective location.
- Integration of centralized seasonal and distributed TESs in a solar DH system is proposed.
- Performance of such integrated solar DH system is evaluated and compared to the one without.
- The integration results in reduction of primary energy consumption and GHG emission.
- The integration improves the overall efficiency of the total solar energy system.

Smart Thermal Grid with Integration of Distributed and Centralized Solar Energy Systems

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Abstract

Smart thermal grids (STGs) are able to perform the same function as classical grids, but are developed in order to make better use of distributed, possibly intermittent, thermal energy resources and to provide the required energy when needed through efficient resources utilization and intelligent management. District heating (DH) plays a significant role in the implementation of future smart energy systems. To fulfil its role, DH technologies must be further developed to integrate renewable resources, create low-temperature networks, and consequently to make existing or new DH networks ready for integration into future STGs. Solar heating is a promising option for low-temperature DH systems. Thermal energy storage (TES) can make the availability of the energy supply match the demand. An integration of centralized seasonal and distributed short-term thermal storages would facilitate an efficient recovery of the solar energy. This study, through modelling and simulation, investigates the impacts of such integration on the overall performance of a community-level solar DH system. The performance analysis results show that

the solar DH system with integration of distributed and centralized seasonal TESs improves system overall efficiency, and reduces DH network heat losses, primary energy consumption and greenhouse gas emissions, in comparison to the one without integration.

Keyword: Smart thermal grid, Solar district heating system, Distributed Thermal Storage, Seasonal thermal storage.

Abbreviation

AH	-	Air handler
BTES	-	Borehole thermal energy storage
CCHT	-	Canadian Centre for Housing Technology
CWES	-	Canadian weather for energy calculations
DH	-	District heating
DHW	-	Domestic hot water
DLSC	-	Drake Landing Solar Community
EF	-	Emission factor
GHG	-	Greenhouse gas
GT	-	Gas tank
HEX	-	Heat exchanger
ICT	-	Information and Communication Technology
PEF	-	Primary energy factor
SEN	-	Smart energy network

SF	-	Solar fraction
SPT	-	Solar preheat tank
STG	-	Smart thermal grid
STTES	-	Short term thermal energy storage
TES	-	Thermal energy storage

Nomenclature

G	-	Solar radiation, W/m^2
$K_{\alpha T}$	-	Incidence angle modifier
Q_{load}	-	Thermal load (space heating and DHW loads), GJ.
Q_{loss}	-	Heat losses from a system, GJ
Q_{solar}	-	Solar energy supplied to a system, GJ
T_a	-	Ambient temperature, °C
T_i	-	Solar collector fluid inlet temperature, °C
η_c	-	Solar collector thermal efficiency
θ	-	Incident angle for beam radiation, °

1. Introduction

The advancement from a smart electric grid to the Smart Energy Networks (SENs) concept has extended the boundary of the smart grid to include all three main energy vectors: electricity, thermal and gas, into one network under a common Information and Communication Technology (ICT) for better management, efficient utilization and increased participation of distributed generation and renewables, and for achieving climate mitigation and energy supply security targets [1-4]. Smart thermal grid (STG) will be an integral element in the future SENs by ensuring a reliable and affordable heating and cooling supply.

Connolly et al. [5] and Lund et al. [6] define the concept of smart thermal grids as a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and/or cooling production units including individual contributions from the connected buildings. Classical thermal grids, or district heating and cooling networks, have a clear distinction between the heating/cooling producer and the heating/cooling consumer, whereas smart thermal grids enable feed-in from consumers (or so called prosumers). These customers then become temporary producers, adding energy to the grid rather than drawing from it. The two-way energy exchange between consumer and the grid, and the ability to manage this intelligently and efficiently distinguishes smart grids from classical grids. Therefore, smart thermal grids will be able to make better use of distributed heat from various renewable energy resources (e.g. solar and geothermal) and industrial surplus heat sources. Schmidt [7-8] summarizes that a smart thermal grid should have the following capabilities: innovative planning and financing schemes, intelligent network operation, customer interaction, cascade usage of resources and integration into the urban energy systems.

According to International Energy Agency report [9], heating and cooling accounted for approximately 46% of the total global energy use in 2012 and district heating (DH) accounts for a major part of this energy consumption [10]. While market penetration of district heating reaches as high as 70% of the heating market in some countries, district cooling has emerged quite recently and is consequently less developed than the district heating market [8].

A number of recent studies [6, 11-18] have investigated the role of district heating in the future smart energy systems based on high penetration of renewable energy as well as substantial reductions in building heating demand. These studies come to the conclusion that district heating plays a significant role in the implementation of future smart energy systems. However, in order to be able to fulfil its role, district heating technologies must be further developed to decrease grid losses, exploit synergies, and thereby increase the efficiencies of low-temperature production units in the system [6] and consequently make existing or new district heating networks ready for integration into future smart thermal grids and smart energy networks.

Solar heating is a promising option for low temperature DH systems and future STGs, but a drawback of solar heating is the mismatch between summer supply and winter demand. Consequently, if solar heat is to supply a significant portion of building heat, thermal energy storage (TES) is a requirement. TES is a bridge to close the gap between the energy demand of a DH system and the energy supply to the DH system [19-20] and is often used for exploiting renewable energy sources [10, 21-22]. Small short-term storage systems can be located inside buildings, but in order to achieve high solar fractions in an economic way, large seasonal storage systems are required. Long term seasonal storage allows thermal energy storage over weeks and months and is particularly important for solar communities where energy availability is much higher in the summer, in contrast to the much higher demand during winters.

Since 1970, the seasonal thermal storage technology, as part of a district heating system, has been under exploration and inspection [23]. Most past and present systems have stored heat in sensible form, since cost is an issue and these systems use mostly water, rocks and soil as storage medium [20]. There are four types of sensible seasonal energy storage in operation: hot water thermal energy storage, gravel-water thermal energy storage, borehole thermal energy storage and aquifer thermal energy storage [23-25]. The selection of a specific store type depends on the geological and hydrogeological situation in the ground at the respective construction site [25]. Based on comprehensive literature review, Rad et al. [23] concluded that borehole thermal energy storage (BTES) has the most favorable condition for long-term energy storage, because the large amounts of energy involvement and relatively low cost of storage media.

Rad et al. [23] and Gao et al. [26] have presented the technical characteristics of some large-scale demonstration plants with thermal collectors and BTES located in Germany (Neckarsulm, Attenkirchen, Crailsheim), Sweden (Anneberg) and Canada (Drake Landing Solar Community). For the mentioned demonstration plants in Germany, the space heating and domestic hot water (DHW) preparation are supplied by the centralised solar plant backed-up by heat pumps (Neckarsulm plant also with backup gas boilers). Anneberg plant in Sweden uses individual electric heaters for providing supplement heat in times when the centrally-stored solar energy is not sufficient to meet the space heating and DHW demands. On the other hand, the centralised solar plant in Drake Landing Solar Community (DLSC) is for supply space heating only, and a separate solar energy system installed for each house is used for DHW preparation. This study is interested in investing the solar BTES system alike the DLSC one and to explore the potential of integration of the centralized and distributed solar thermal energy storage systems.

The Drake Landing Solar Community in Canada is a planned neighbourhood with 52 R-2000 single family homes, in the town of Okotoks, Alberta, equipped with a central solar district heating system with short- and long-term (seasonal) thermal energy storages. Systems of similar size and configuration have been constructed in Europe, however, this is the first system of this type designed to supply more than 90% of the space heating with solar energy and the first operating in such a cold climate (5200 degree C-days) [27]. In 2012 (after 5 years in operation), the system achieved a world record solar fraction of 97%, and a reduction of approximately 5 tonnes of greenhouse gas (GHG) emissions has been attained per home per year compared to those with conventional heating systems [28]. To meet domestic hot water (DHW) demands, every home in the Drake Landing Solar Community is equipped with two unique, self-regulated solar panels on the roof of the house. These solar panels are connected to a solar hot water tank in the basement. On an annual basis, approximately 60% of the home’s domestic hot water requirements are met using solar energy [29]. When solar energy is not available, the hot water demands are supplemented by a back-up natural gas, power-vented hot water tank unit.

Typically domestic hot water demand peaks in the morning and evening, and there is little or even no usage (e.g. for working family with school-age children) during the day. In this case the solar energy available/sufficient in the daytime will not be fully collected due to the limitation of the solar hot water storage tank capacity/volume. One way to further improve the efficiency of the local distributed solar systems is to integrate them to the centralized DH system for space heating at times there is no or low DHW demand. The energy from the centralized DH centre will be drawn to top-up the space heating demand when it is required. In this way, the capacity of the distributed solar systems will be fully utilized, and in addition, the frequency of calling energy transfer from centralized short term energy storage and BTES to each home will be lowered. It is expected that the pumping power to move the energy from and back to the centralized solar energy plant as well as the network heat losses will be reduced.

This study is to investigate the impacts of integration of local distributed solar storage system with centralised long-term storage system on the overall performance of a community-level solar district heating system; and to develop modelling tools that can be used for the optimization of solar thermal storage applications ready for inclusion in the future smart thermal grids and smart energy networks.

2. Solar district heating systems for case studies

An alternative solar district heating system, with the interaction of the local solar energy system to the centralized solar district heating system, is proposed for case study. Its performance will be compared to a reference system that is DLSC like district heating system.

2.1. Configuration of reference solar district heating system

The Reference system for the case study is shown in Fig. 1. The solar energy captured by solar thermal collectors (flat-plate) is first transferred, through a heat exchanger (HEX1), into a Short Term Thermal Energy Storage (STTES) tank. From there, if there is a heating demand, the thermal energy is transferred through another heat exchanger (HEX2) into the distribution networks, and then to end-users for space heating. This mode results in the least loss of exergy. If the energy is not immediately required, it is moved to the long-term energy storage system, BTES. When heating demand returns, it can be recovered from there, albeit at a lower temperature than when it was deposited. Backup boilers are used to supplement the space heating demand when the solar energy collected and stored in the short- and long-term storage systems cannot meet the energy requirement.

Fig.1. Schematic of Reference System (System1) for Case Study.

The short-term energy storage is the interface of the energy source, the long-term thermal energy storage and the energy distribution system. Without the STTES, the power from the collectors would have to be absorbed by the long-term borehole thermal energy storage even at peak collection times. This would result in very large underground heat exchangers and requiring more boreholes than with the use of the STTES. Hence the STTES is critical to the proper operation of the entire system, because it can accept and dispense heat at a much higher rate than the BTES storage which in contrast has a much higher capacity [27].

Every home is equipped with self-regulated solar panel on the roof of the house for domestic hot water heating. These solar panels are connected to a solar preheat hot water tank in the basement. The energy stored in the preheat tank is then transferred (through a low-flow circulation pump) to a gas-fired hot water storage tank for DHW draws. When solar energy is not available/enough, the hot water demands are supplemented by the gas-fired hot water tank. A tempering valve is used to maintain the domestic hot water temperature at a predetermined level.

2.2. Configuration of proposed system with integration of distributed solar heating systems

The proposed alternative solar energy system, which integrates local distributed solar DHW energy system with the centralized short-term and long-term thermal energy storage systems, is illustrated in Fig. 2.

Fig.2. Schematic of Alternative System (System 2) for Case Study.

In this case, the local solar system is used for space heating at times there is no or low DHW demand. The heat stored in the hot water tank (in house basement) is transferred to the fan-coil through a heat exchanger. The energy from the centralized DE centre will be drawn to top-up the space heating demand when it is required. In this way, the capacity of the local solar DHW system will be fully utilized. It is expected that the frequency of calling energy transfer from the centralized storage systems to each home will be lowered and consequently the network heat losses and pumping power will be reduced.

2.3. Community served by the solar district heating system

It is assumed that the solar district heating system supplies thermal energy to a group of 50 detached 2-story single family houses for space heating. The community is assumed to be located in Ottawa, Ontario. Each house has a total floor area of 210 m^2 and is built to meet Canada's R-2000 Standard [30]. The annual heating load (at room temperature of 21°C) is approximately 55 GJ/house. The domestic hot water consumption is assumed at 252 L per day (or 16 GJ/yr) per household [31].

2.4. Simulation Cases

The performance of the Reference System (System 1) and the alternate system (System 2) are simulated and compared. Since System 2 integrates distributed and centralized solar heating systems, it is expected that the size combination of the centralized and localized systems will have an impact on the overall performance. Therefore five cases (2A-2E as listed in Table 2), which with different combination of borehole sizes, collector numbers and storage tank volumes, were investigated.

Table 1. Simulation Cases.

Despite the configuration difference between the Reference system and System 2A, the size of each component is assumed to be the same. In this way, the impact from the configuration change alone can be evaluated.

In System 2B, the number of collectors in the centralized solar field is reduced to 700, but the distributed solar panels installed on the roof of each house are increased to 4. However, the total number of solar collectors is remained the same at 900. The purpose of this case is to evaluate the impact of the distributed solar energy collection capacity on the performance of the entire solar energy system.

It should be noted that, for System 2B, the solar energy collection capacity of the distributed solar system is limited as the volume of the solar preheat tank is remained the same, despite the increase of the solar panels on the roof. In order to maximize the solar collection of the distributed solar heating system, the solar preheat tank volume installed in the house basement should be enlarged as well along with the increases of the solar panels. Hence, in System 2C, the solar preheat tank volume is increased from 200 L to 400 L.

As the number of solar collectors for the centralized system is reduced, it is anticipated that the borehole field size can be decreased as well thereby to save the initial capital cost. Hence, in systems 2D and 2E, the borehole size is reduced to 132 and 126 boreholes respectively.

3. Modelling methodology and control approach

3.1. Modelling methodology

A TRaNsient SYstems (TRNSYS) software platform [32] was used to model and analyze the six cases presented in the previous section. TRNSYS is developed by University of Wisconsin and is one of the most popular advanced dynamic building energy simulation programs. In the present study, component modules were selected from the TRNSYS libraries. The main component modules (called "Types" in TRNSYS terminology) include: building, vertical ground heat exchanger (BTES), solar collector, hot water storage tanks, air handlers, plate heat exchangers, gas fired boiler, distribution pipes, variable speed pumps, valves, and controllers. Major component models were enhanced by manufactures' performance data or validated by field/experimental data prior to performing simulations.

TRNSYS Type 557 (vertical ground heat exchanger) was used to model the BTES. It is considered to be the state-of- the-art in dynamic simulation of ground heat exchanger that interacts thermally with the ground. Type 557 has been used by various researchers for modelling energy systems with BTES [33-36].

Type 56 (multi-zone building model) was used to model the houses. In the present study, the house model was based upon the twin research houses of the Canadian Centre for Housing Technology (CCHT) in Ottawa [30, 37] and calibrated against measured data [38].

Flat-plate solar collectors were modelled using TNSYS type 1b. In this component model, the collector efficiency (η_c) was modeled by a second-order equation (Eq.1), and correction for off-normal solar incidence is applied by a second-order incidence angle modifier ($K_{\alpha T}$) equation (Eq.2). The coefficients (in SI units) listed in the two equations were based on manufacturer specifications for a single flat-plate collector with gross area of 2.9 m^2. The solar collectors were assumed to be installed at the optimum angle for the investigated location (37° for Ottawa, Canada) [38].

$$\eta_c = 0.717 - 4.033\frac{(T_i - T_a)}{G} - 0.0184\frac{(T_i - T_a)^2}{G} \quad (1)$$

$$K_{\alpha T} = 1.0 - 0.11S - 0.0506S^2 \quad (2)$$

where T_i is fluid inlet temperature, T_a is ambient temperature and G is solar radiation. In Equation 2, $K_{\alpha T}$ is incidence angle modifier and S=1/cosθ - 1 (θ is the incident angle for beam radiation).

While TRNSYS Type 534 (cylindrical storage tank) was used to model the vertical storage tanks in the distributed solar systems, Type 533 (horizontal cylindrical storage tank) was used to model the short term thermal energy storage (STTES) tank in the centralized solar system.

Air handlers were modeled by TRNSYS type 753d (free-floating coil). This air handler model employs a bypass fraction approach and does not attempt to control the air and water temperatures. It was validated by performance data from a commercially available air handler. Plate heat exchangers were modeled by TRNSYS type 761 and type 512 for HEX1 and HEX2 respectively (c.f. figures 1 and 2).

The dynamic properties of district heating networks include water flow and propagation of heat from production plants to consumers. One type of mathematical model involves a full physical modeling of the network, taking into account individual pipes, dimensions, material properties etc. Such full models tend to be computationally intensive when applied in network simulations, which can be a problem when considering large DH systems. Hence, DH networks are often modeled using aggregated method [39-41]. In the aggregated method, the topological complexity of a DH network is reduced by gradually changing a tree structure into a chain structure with no branches, while still preserving the most important physical properties of the original network. The various parameters which define the branches are transformed from the real network to equivalent parameters in the corresponding equivalent network. Thus a simple network description is sought, which is nearly equivalent to the original one. In this study, an equivalent network with a single pair of DH supply and return pipes is used to represent the DH network. Each pipe has a length of 400 m and a diameter of 0.8 m. The network model is used to calculate the heat losses from the DH pipes and required pumping power for transporting the DH water to the end-users (houses). TRNSYS type 31 was used to model the DH distribution pipes.

All pumps in the system were modeled by TRNSYS Type 977 (variable-speed pump). The DH pump operates continuously with flow rate varying between 1200 L/h and 24,000 L/h in the heating season. The DH water flows through the house air handler only in cases when there is a call for heat by the house thermostat. When there is no heat demand, the DH pump operates with the minimum flow rate to avoid a significant temperature drop in the DH network.

3.2. Control and operation strategies

The control and operation strategies used in the simulation studies for the solar district heating systems are presented in Table 2.

Table 2 Control Algorithms and Strategies.

It should be noted that the set-point for DH supply temperature varies between 55°C and 40°C based on the ambient temperature. It is proportional to the ambient temperature between the -35°C and -5°C range. The DH supply temperature will be kept at 55°C if the ambient temperature is lower than -35°C, or at 40°C if the ambient temperature is above -5°C. If the stored solar energy is not sufficient to heat the DH supply to its set-point, backup boilers will provide the supplement energy. The boiler thermostat is assumed to have a dead band of 4°C.

If the energy stored in the short-term storage tank is not immediately required, it is moved to the centre of the borehole thermal energy storage. The BTES charging control algorithm is different in winter heating season and in summer when there is no heating requirement as shown in Table

2. However, the BTES discharging is the same both in the winter and summer. When heat demand returns (e.g. in fall), the energy stored in the BTES field will be withdrawn from its outer edge.

When there are heat demands from the end-users, the distribution network pump will be running to transfer heat to the houses. The call for heat is triggered by the thermostat installed in each house. The room temperature is targeted to be kept at 21°C. For the Reference system, when the room temperature is lower than 20.5°C, it calls for heat from the solar energy centre. For the alternate system (System 2), however, the call for heat is enabled when the room temperature falls below 19.5 °C in order to first utilize the solar energy stored in the distributed (local) tanks in each house. The call for heat signal will be disabled when the room temperature reaches 21°C. In the alternate system, System 2, the distributed storage system is utilized at times when there is no or low DHW demand. The control algorithm is developed in a way that the energy will be drawn from the local (distributed) solar system first, then from the centralized solar energy center. The AH pump circulates water from the gas-fired tank to the air handlers to heat up house circulation air. The pump is activated if the room temperature is lower than 20.5°C and is turned off when the room temperature reaches 21°C, or the temperature nearby the gas tank top (tank node 2) drops below 47°C.

The DHW temperature is assumed to be at 55°C. In order to maintain the water temperature at gas tank top higher than 55°C, the burner at the bottom of the storage tank is fired if the temperature nearby the top (tank node 2) is less than 45°C until this temperature exceeds 60°C or the temperature nearby the bottom (tank node 8) reaches 50°C. The domestic hot water is drawn from the gas fired tank and there is a tempering valve to maintain the DHW temperature not to exceed 55°C.

3.3. Weather data and simulation period

The weather data used in the simulations are from Canadian Weather for Energy Calculations (CWEC) database in EnergyPlus format [42]. The heating season is assumed to start from October to May with the cooling season from the beginning of June to the end of September.

4. Results and discussion

Energy and emission analyses are conducted based on the simulation results obtained from the developed TRNSYS simulation models. The results are presented in the following sections. It should be noted that the simulation results are from the fifth year operation after the BTES field is fully charged.

4.1 Thermal loads and heat losses

Fig. 3 shows the annual space heating and DHW loads, and the heat losses from the DH network and the distributed solar systems for the six cases investigated. The heat losses from the distributed solar systems include the losses from the storage tanks and pipes installed in the basement of each house.

Fig.3. Annual Thermal Loads and Heat Losses of DH Network and Distributed Solar Systems.

The annual space heating load is approximately 54.6 GJ/house and the DHW hot load is 16.1 GJ/house. It should be noted that the loads as shown in Fig. 3 are slightly different from case to case due to the effect of the thermostat or aquastat dead-band.

The annual heat losses from the DH network for the Reference system and systems 2A-2E are ranging from 125 GJ to 110 GJ. The results show that the heat loss from the DH network of System 2 is more than 11% lower compared to the Reference system. Since System 2 utilized the distributed solar system in each house for space heating, the demand, and also the frequency, for transporting thermal energy from the central solar system is reduced. Thereby it reduces the DH network heat losses.

The annual heat loss from the distributed solar system is 39 GJ for the Reference system. Comparing to the Reference system, Systems 2A-2E have lower heat losses (20% to 58% lower) from the distributed solar system. This is because, for the Reference system, its distributed solar system is designed solely for DHW heating, thus it has higher heat losses from the two storage tanks resulting from prolonged standby periods between DHW draws. Conversely, System 2 utilizes the distributed storage system for space heating, thus reducing the heat losses from the storage tanks in time periods when there are no DHW draws.

However, due to the increase of the solar panels and solar preheat tank volume for systems 2B-2E, their annual heat losses are higher compared to System 2A (increasing to 22 and 31 GJ from 16 GJ).

Overall, systems 2A-2E reduced the annual total heat losses by 13 to 22% compared to the Reference system. As a result, the annual total thermal energy load is reduced from 3715 GJ for the Reference system down to 3651 GJ for System 2A, to 3668 GJ for System 2B and to 3671 GJ for systems 2C-2E (c.f. Fig.3).

As shown in Fig. 3, the total thermal load reduction resulted from the integrating distributed solar systems is ranged from 1.2% to 1.7%. It is also observed that the space and DHW heating loads of the proposed systems 2A-2E are slightly lower (0.3%-0.6%) than that of the Reference system due to the effect of thermostat or aquastat dead-band as well as small control differences between the systems as a result of altered configurations. Thus the overall load reduction (%) could be less than the values stated above. However, it is worth noting that the scale of the system investigated (for 50 houses) is much smaller than the economic optimum [34], and in general, solar energy system with seasonal thermal storage is more cost effective in large scale. With regards to this factor, even a small percentage load/heat loss reduction can result in significant amount of energy and operational cost savings, and therefore cannot be overlooked or disregarded.

4.2 Space heating load met by distributed solar energy systems

In the Reference system, all of the space heating requirements were supplied by the centralized solar DH system. On the other hand, systems 2A-2E integrate the distributed solar energy systems to the centralized solar DH system for satisfying a fraction of the space heating load, thereby to enhance the utilization of the distributed thermal storage. Based on the simulations results, the amount of space heating load met by the distributed solar systems is calculated and show in Table 3 on monthly and annual basis. Also shown in the table is the percentage (%) of the total monthly/annual space heating load that was covered by the distributed solar systems. It should be mentioned that the entire DHW heating load (approximately 805 GJ/year, or 16.1 GJ/house/year) was met by the distributed solar systems.

Table 3 Monthly Space Heating Load Met by Distributed Solar Thermal Storage Systems.

As it can be seen from the figure, the distributed solar systems can cover approximately 89 to 146 GJ space heating load annually (i.e. approximately 3.3% to 5.3% of the annual total space heating load of the 50 houses). System 2A, which has the same size as the Reference system with 2 solar panels for each house, has the lowest percentage of the space heating load met by the distributed solar system.

In shoulder season (October, March and April) the distributed solar systems can meet 6% to 12% (9.8 to 33.3 GJ), and in May it can satisfy 19% to 43% (4.6 to 10.4 GJ) of the monthly total space heating load depending on the system design. In winter season (November, December, January and February), the distributed solar systems can meet approximately 1% to 5% (7.7 to 24.2 GJ) of the total space heating load due to high heating load as well as low solar radiation during these time-periods.

As shown in Table 3, systems 2C-2E can satisfy the same amount of the space heating load. The three systems have increased number of collectors (4 collectors per house) in the distributed solar systems but reduced number of collectors (total 700) in the centralized solar system. The reduction of the borehole numbers in systems 2D and 2E does not affect the percentage amount of space heating load met by the distributed solar systems.

For System 2B, the distributed solar systems provide the highest amount of the space heating load in every month, except in May. In this system, the number of the solar collectors for each house is increased, but the solar tank volume is remained the same. It is expected that, when there is solar radiation during the day, the water temperature in the storage tanks is higher than that of the other systems with larger storage volume (systems 2C-2E). This enables the distributed solar system to draw more energy for space heating. On the other hand, it also reduces the stored energy for DHW heating which typically occurs in the evening and morning. Thereby, it requires the gas burner in the storage tank to provide supplement heat for the DHW heating. As illustrated in Fig. 4 in the next section, the distributed solar system in System 2B has the highest natural gas consumption in comparison to other proposed systems (2A and 2C-2E).

4.3 Primary energy consumption

Fig. 4 presents the primary energy consumption calculated based on the usage of electricity and natural gas respectively for the six cases investigated. The overall primary energy savings (in %) achieved from the alternative systems are also shown in the figure. Although the primary energy factor (PEF) for electricity from the grid varies depending on the generating mix in any given year, they were assumed at 2.6. The primary energy factor for natural gas was assumed at 1.1 to consider 10% of overhead for delivering to the site.

Fig.4. Annual Primary Energy Consumption.

The primary energy consumption from the electricity usage is 797 GJ/yr for the Reference system and ranged from 760 to 764 GJ/yr for the systems with integration of the distributed solar systems. The simulation results show that the electricity consumption of the centralized DH system pumps is decreased due to the utilization of the distributed solar thermal storage. On the other hand, the pumping energy consumption of the local solar systems is increased due to additional pumps in each distributed system. Overall, the total electricity consumption of systems 2A-2E is approximately 1% lower than that of the Reference system.

As shown in the figure, the annual primary energy consumption from natural gas usage is at 724 GJ for the Reference system and is in the range of 691-790 GJ for systems 2A-2E. The percentage reduction is between 1% and 13%, which again is resulted from the use of the distributed solar thermal storage systems.

Overall, the annual total primary energy consumption of the systems which utilizing distributed solar systems (System 2A-2E) is less than that of the Reference system and ranges from 1455 to 1550 GJ. The alternate systems result in primary energy saving of 1% to 7%. Systems with both increased distributed solar panels and thermal storage (System 2C-2E) have higher primary energy savings. Although System 2C consumes less primary energy compared systems 2D-2E, it is expected that the first system has higher initial capital cost than that of the two later systems due to its larger borehole field.

4.4 *Overall system performance*

The overall system efficiency is shown in Fig. 5. The efficiency is defined as the ratio of the total thermal load to the total primary energy input. The thermal loads and primary energy input are also shown in the figure. The thermal loads, which have been discussed in Section 4.1, include the houses' space heating load, DHW load, and the heat losses from the DH network as well as from the distributed solar storage systems. The total primary energy input includes those from the electricity, natural gas and solar.

Fig.5. Overall System Performance.

As it can be seen from the figure, the alternate systems (2A-2E), which integrate distributed thermal storage to the centralized solar system, have better performance in comparison to the Reference system. The Reference system has an overall efficiency of 80.6%, and systems 2A-2E have an overall efficiency ranging from 81.9% to 82.2%.

4.5 Solar fraction

Fig. 6 shows the annual solar fraction for the centralized and distributed solar system, as well as for the entire system. The solar fraction is calculated by the following equation:

$$SF = \frac{Q_{solar}}{Q_{load} + Q_{loss}} \quad (3)$$

Where Q_{solar} is the solar energy supplied to the DH network, or the distributed solar systems or the total system; Q_{load} is the space heating and DHW loads, and the Q_{loss} is the heat losses from the DH network or the distributed solar systems, or the total system.

Fig.6. Solar Fraction of Centralized, Distributed and Entire Solar Systems.

The solar fraction of centralized solar system is 86% for the Reference system as shown in Fig. 6. For systems 2A-2E, the solar fraction is slightly lower, ranging from 79.9% to 85.5%. For these systems, the solar energy collected by the centralized system sometimes is not required to be used immediately due to the usage of the distributed solar systems for meeting partial space heating loads. Additionally, systems 2B-2E have less collectors in the central solar field and systems 2D-2E have smaller borehole storage capacity. These are also the attributing factors for solar fraction reduction of the centralized solar system.

The solar fraction of the distributed solar system is 68.2% for the Reference system. However, the solar fraction increases to 73.3-82.6% for distributed systems with increased solar panels and thermal storage volume (systems 2B-2E). It is observed that, for System 2A which has configuration changes only compared to the Reference system, the solar fraction is reduced to 64.0%. This is because, for System 2A, the load imposed on the same distributed solar system (which includes DHW load and partial space heating load) is higher in comparison to the Reference system.

The solar fraction for the overall system ranges from 79.9% to 82.0%. System 2C has the highest solar fraction and the rest of the systems have slightly lower solar fraction.

It should be noted that, in general, solar fraction of a system does not reflect the system effectiveness. There are other metrics, such as system efficiency and cost, including initial and operating, that needed to be taken into account for comparing different installations [23].

4.6 Greenhouse gas emission

The greenhouse emission from the systems investigated is calculated and compared. The natural gas emission factor (EF) used in the calculation is 1888 g/m3 (50.4 kg/GJ) for Ontario [43]. The electricity emission factor used in the calculation is 106 g/kWh (29.4 kg/GJ) for Ontario [44], which is calculated based on the three-year average values reported in the 1990-2012 Canada National Inventory Report (Part 3) [45].

Fig. 7 presents the greenhouse emission results for all systems investigated. The results show that all the alternate systems achieve the greenhouse gas emission reduction by 1% to 11%. Again systems with increased distributed thermal storage and solar panels (2D-2E) have higher emission reduction in comparison to system 2A and 2B.

Fig.7. Annual Greenhouse Gas Emission.

4.7 Discussion

The performance analysis results clearly show that integrating the distributed solar thermal storage system for space heating has the following advantages:

- Reduce heat losses from the district heating network (11% to 12%);
- Reduce heat losses from the distributed solar systems (20% to 58%);
- Reduce overall pumping electric energy consumption (0.8% to 1.2%);

- Reduce overall natural gas consumption (0.9% to 13.3%);
- Reduce primary energy consumption (1% to 7%);
- Reduce greenhouse gas emission (1% to 11%);
- Improve the overall system performance;
- Maximize the utilization of the distributed solar thermal storage system.

However, the degree of saving or reduction is dependent on the combination of the size of the centralized and distributed solar systems. The study found that the system with configuration change only (without sizing changes compared to the Reference system) can achieve both energy and greenhouse emission savings but not significant. In order to supply heat more effectively as it is needed and thereby achieving higher savings, the number of solar panels and thermal storage capacity in the distributed systems should be increased at the same time. To avoid the initial capital cost rise resulted by this change, the number of solar panels in the centralized system should be reduced accordingly. This indicates that it is important to conduct optimization studies in the design and planning processes, so the distributed solar energy systems are integrated in a cost-effective way in the total energy system.

In general solar energy system with seasonal thermal storage is more cost effective in large scale. With regards to this factor, a small percentage load/heat loss reduction can result in significant amount of energy and operational cost savings, and therefore cannot be overlooked or disregarded.

5. Conclusions

Smart thermal grid will be an integral element in the future SENs by ensuring a reliable and affordable heating and cooling supply. STGs are able to perform the same function as classical or regular grids, but are developed in order to make better use of distributed, possibly intermittent thermal energy resources and to provide the required energy when needed through efficient resources utilization and intelligent thermal grid management.

Solar heating is a promising option for low temperature DH systems and future STGs. Thermal energy storage systems can make the availability of the energy supply match the demand. Smart thermal grid should be designed in a way to store energy in the most efficient manner at the most effective location. Therefore an integration of centralized seasonal and distributed (local) short-term thermal storages would facilitate an efficient recovery of the solar energy and to meet peak demands at much lower network flows.

This study investigated the impacts of integration of local distributed solar storage system with centralised short- and long-term storage systems on the overall performance of a solar district heating system. The performance analysis results show that the solar DH system with integrated distributed and centralized seasonal thermal storages improves system overall efficiency, results in reduction of heat losses from the distribution network, overall pumping power consumption, auxiliary natural gas consumption and greenhouse gas emissions, in comparison to the one without integration.

The degree of saving or reduction is dependent on the size combination of both centralized and distributed solar systems. Therefore, optimization studies should be conducted in the design and planning processes to ensure the distributed solar energy systems are integrated in a cost-effective way in the total energy system. Future work will include cost analyses and optimization studies.

Acknowledgment

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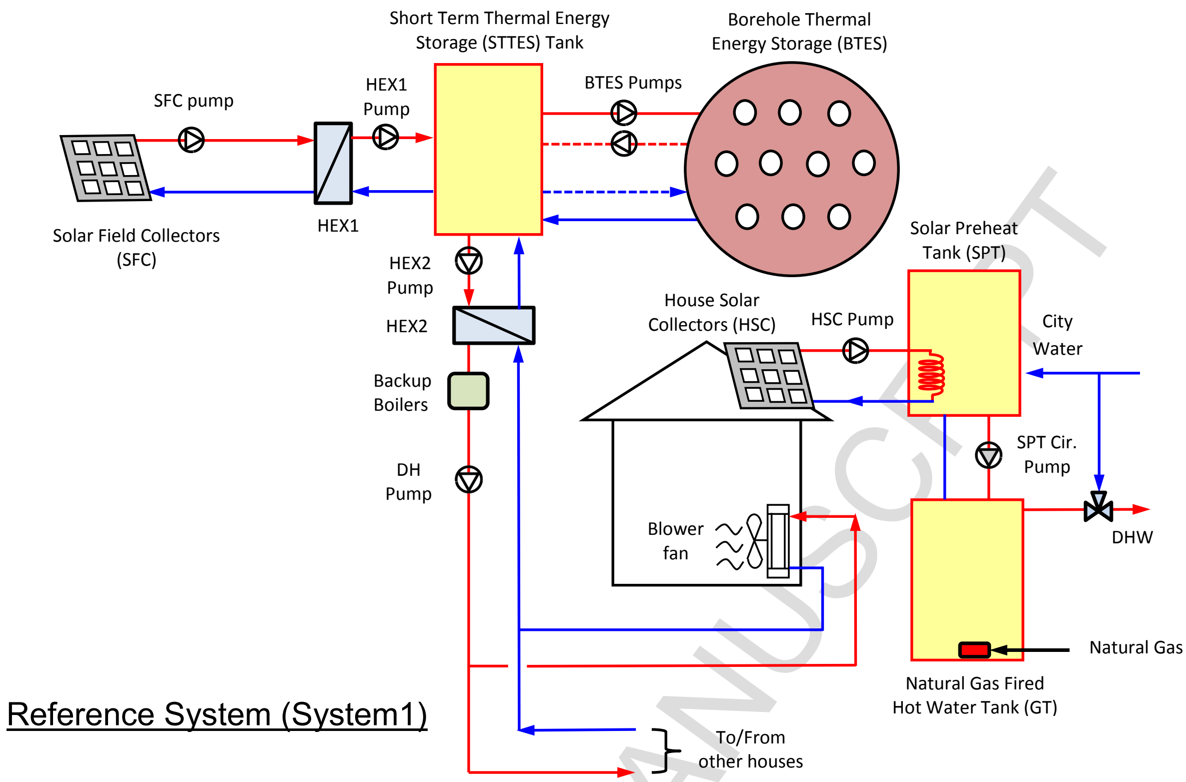

Fig.1. Schematic of Reference System (System1) for Case Study.

Full page layout

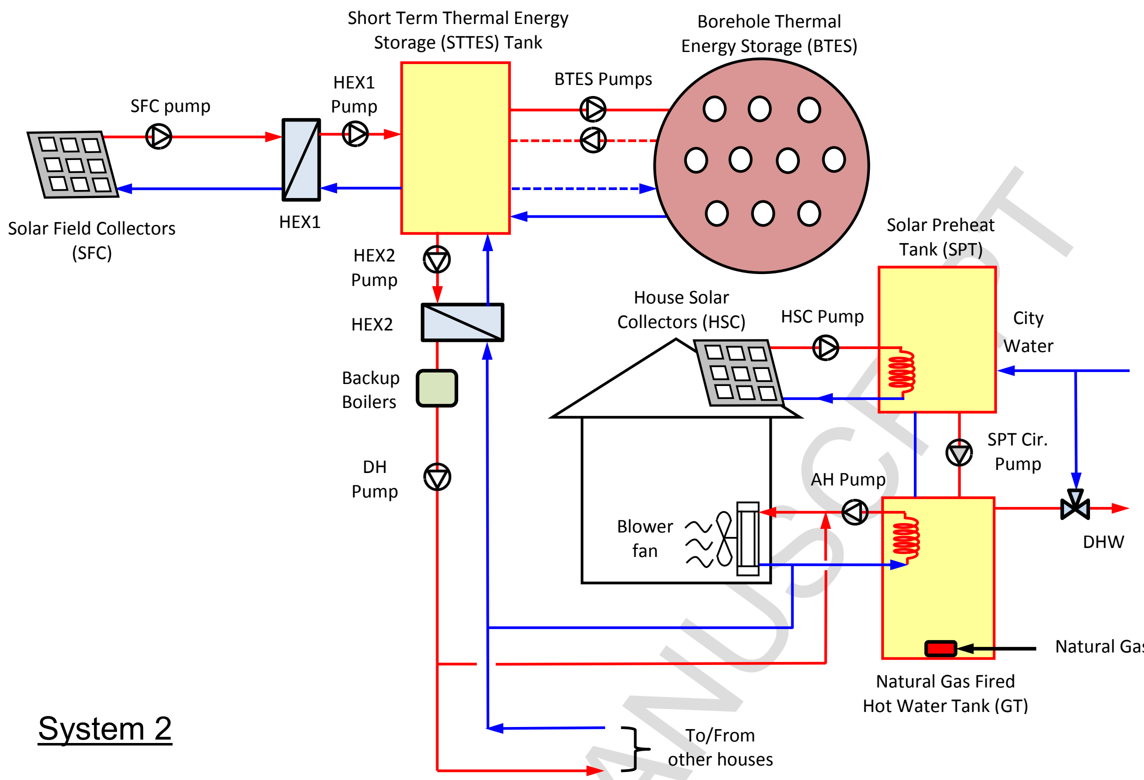

Fig.2. Schematic of Alternative System (System 2) for Case Study.

Full page layout

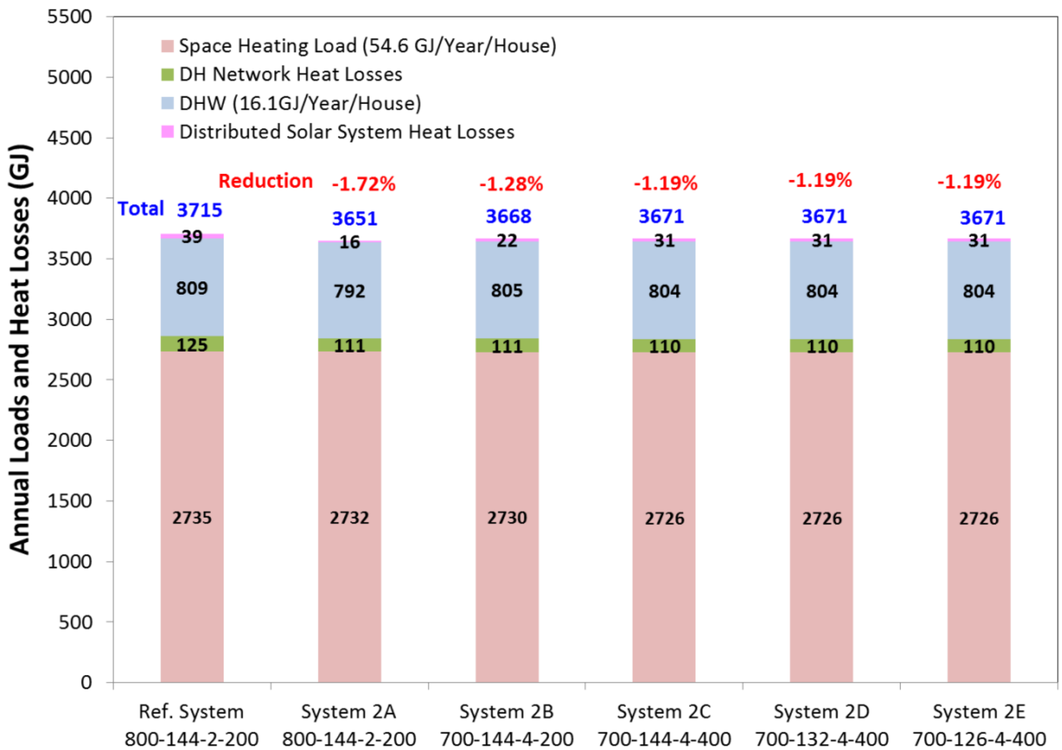

Fig.3. Annual Thermal Loads and Heat Losses of DH Network and Distributed Solar Systems.

Full page or half page layout

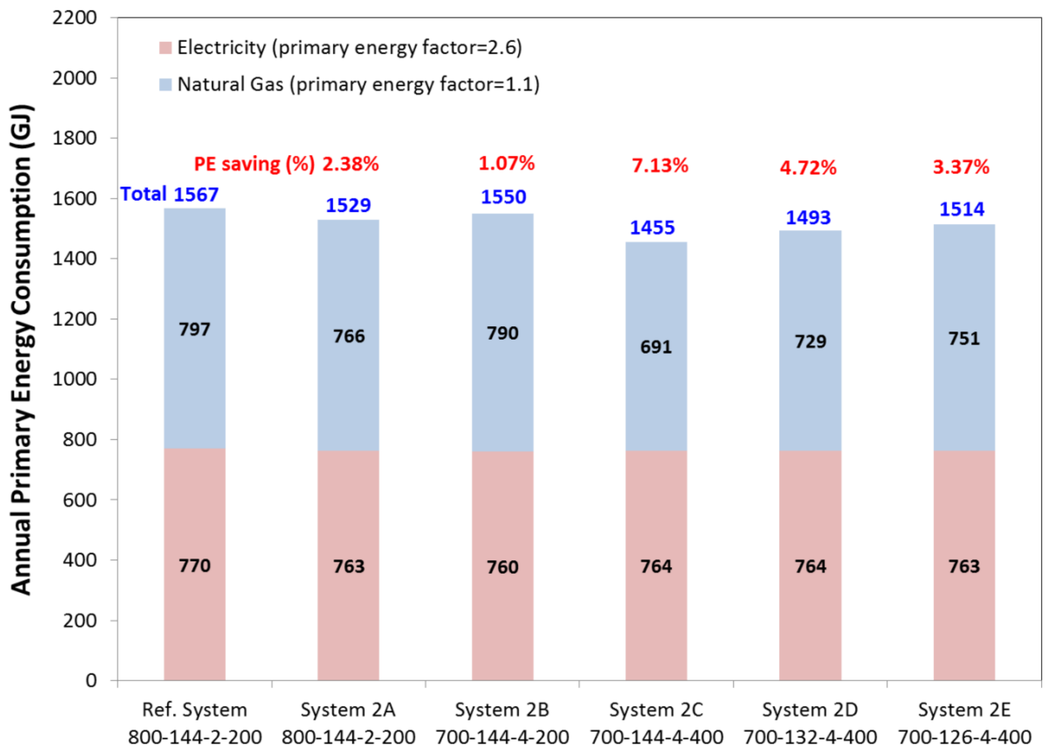

Fig.4. Annual Primary Energy Consumption.

Full page or half page layout

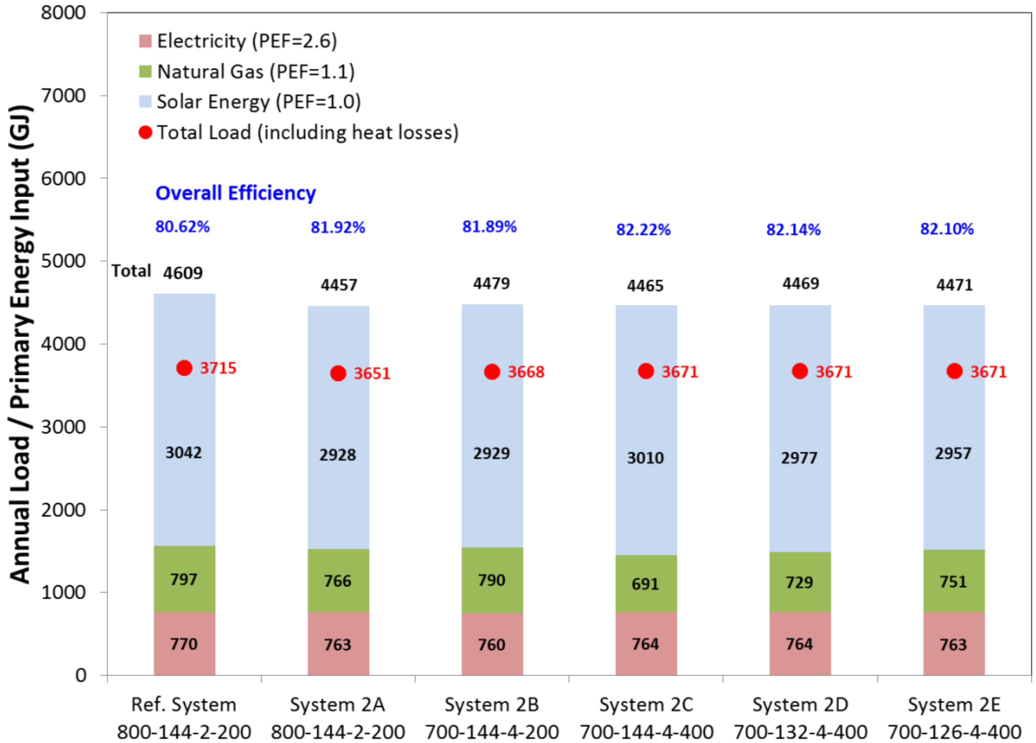

Fig.5. Overall System Performance.

Full page or half page layout

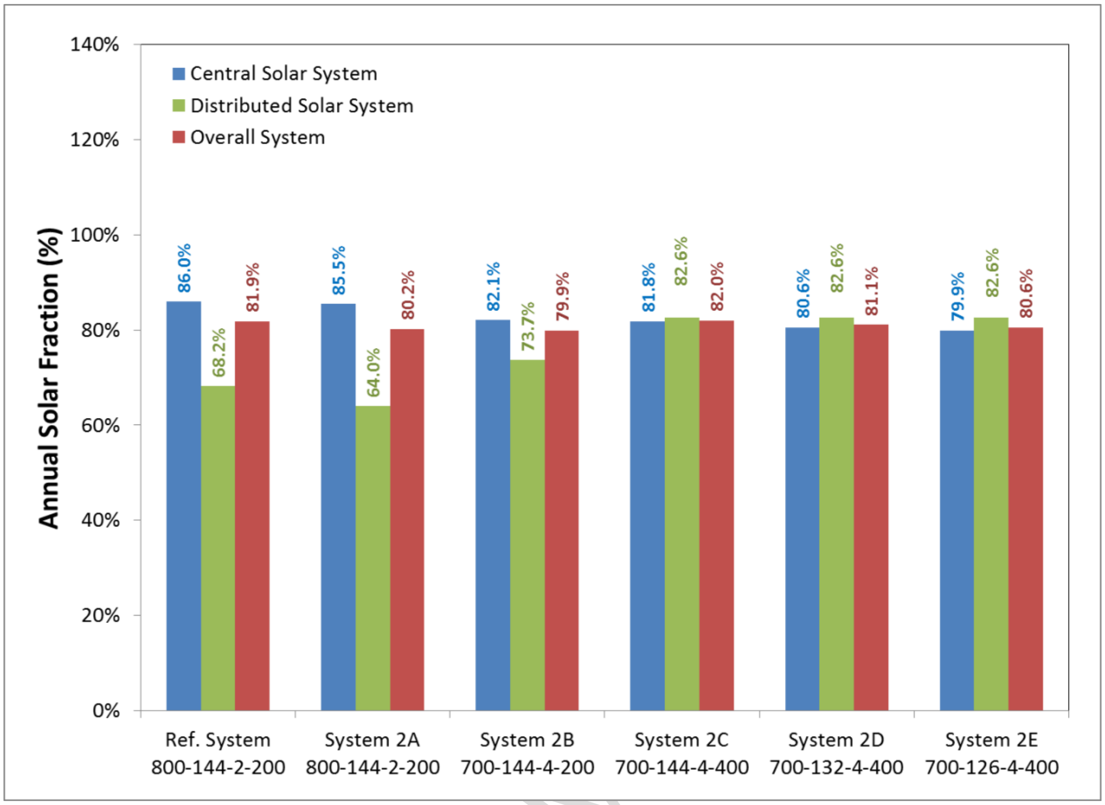

Fig.6. Solar Fraction of Centralized, Distributed and Entire Solar Systems.

Full page or half page layout

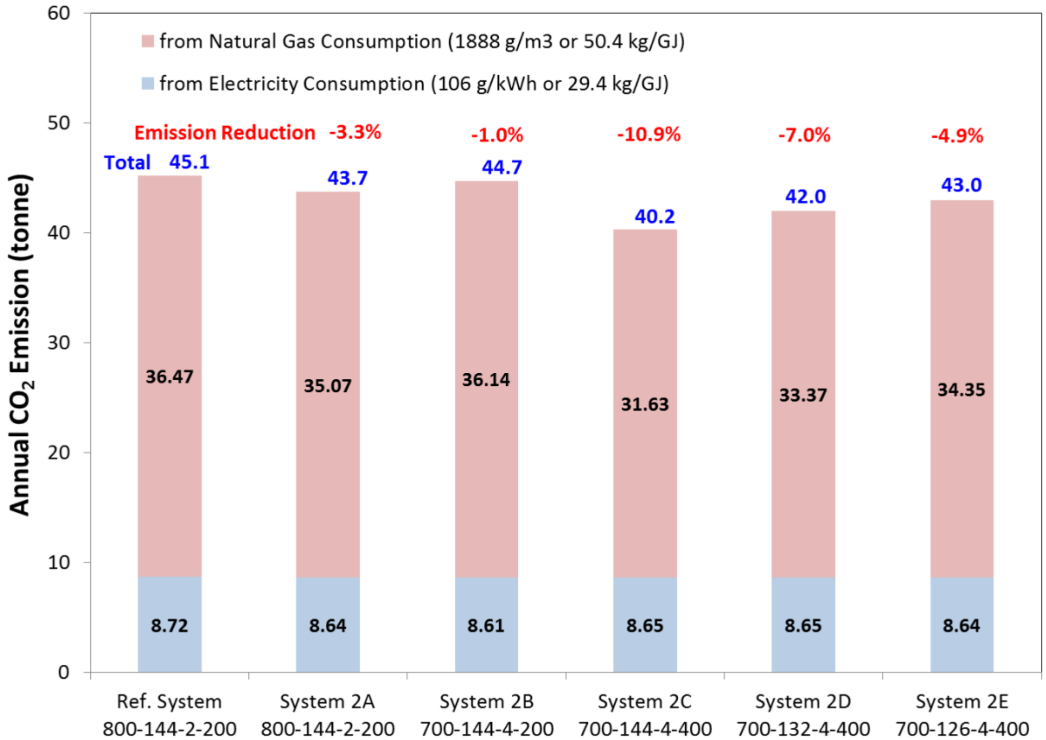

Fig.7. Annual Greenhouse Gas Emission.

Full page or half page layout

List of table captions:

	Ref. System	System2 A	System2 B	System2 C	System2 D	System2 E
Centralised solar district heating system						
Number of boreholes [a]	144	144	144	144	132	126
Borehole depth (m)	35	35	35	35	35	35
Number of solar collectors –centralized [b]	800	800	700	700	700	700
STTES tank volume (m^3) [c]	240	240	240	240	240	240
Backup boiler capacity (kW) [c]	460	460	460	460	460	460
Distributed solar heating system (per house)						
Number of solar panels	2	2	4	4	4	4
Solar preheating tank volume (L)	200	200	200	400	400	400
Gas fired hot water storage volume (L) [c]	200	200	200	200	200	200

[a]: *single u-tube boreholes, each parallel circuit with 6 boreholes in series.*
[b]: *flat-plate solar thermal collectors, each parallel array with 20 panels in series.*
[c]: *the size for these components are remained the same for all simulated cases.*

Table 1. Simulation Cases.

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Centralized Solar Energy System		ON	OFF
Solar field pump		T(panel) –T(btm_STTES) >= 10°C	T(panel) –T(btm_STTES) <= 2°C OR T(top_STTES) >= 90°C
HEX1 pump		HEX1 cold side fluid temperature difference is maintained at 12°C	
HEX2 pump		Flow is controlled by pre-set DH supply temperature	
BTES charging pump	Charging (Winter)	T(btm_STTES) – T(DH_set) >= 10°C AND T(top_STTES) > T(ctr_BTES)	T(btm_STTES) – T(DH_set) <= 2°C OR T(top_STTES) <= T(ctr_BTES)
	Charging (Summer)	T(top_STTES) – T(ctr_BTES) >= 10°C AND T(avg_BTES) <= 90°C	T(top_STTES) – T(ctr_BTES) <=3°C OR T(avg_BTES) > 90°C
BTES discharging pump	Discharging	T(ctr_BTES) – T(btm_STTES) >= 10 °C AND T(top_STTES) <= 55°C	T(ctr_BTES) – T(btm_STTS) <= 3 °C T(top_STTES) > 55°C
DH network pump	System1 (Ref.)	T(room temp) <=20.5°C	T(room temp) >= 21.5°C
	System 2	T(room temp) <=19.5 °C	Troom temp >= 21.5°C
Central backup boiler		T(DH_set) - 2°C	T(DH_set)+2°C
Distributed Solar Energy System		**ON**	**OFF**
House solar collector pump		T(panel) –T10(solartank) >= 10°C	T(panel) –T10(solartank) <= 3°C OR T1(solartank) >= 90°C
Solar preheat tank circulation pump		T1(solartank) – T10(gastank)>=7°C	T1(solartank) – T10(gastank)<=2°C OR T1(gastank) > 70°C
Gas tank burner		T2(gastank) <= 45°C	T8(gastank) >= 50°C OR T1(gastank) >= 60°C
AH pump	System 2 only	T(room temp) <= 20.5°C	T(room temp)>=21°C or T2(solartank)<47°C

Note:
T(btm_STTES) – Temperature at STTES tank bottom. *T(top_STTES) – Temperature at STTES tank top.*
T(ctr_BTES) – Centre temperature of borehole field. *T(avg_BTES) – Average temperature of borehole field.*
T(DH_set) – DH supply temperature set-point. It is a function of ambient temperature. *T(panel) – Fluid temperature in solar panel.*
T1(tank), T2(tank), … T10(tank) are the temperature sensors in tank node1, 2, …, and 10 respectively. Each storage tank is divided into 10 isothermal nodes, 1 at the tank top and 10 at the tank bottom.

Table 2 Control Algorithms and Strategies.

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System	System 2A 800-144-2-200		System 2B 700-144-4-200		System 2C 700-144-4-400		System 2D 700-132-4-400		System 2E 700-126-4-400	
	GJ	% of total	GJ	% of total	GJ	% of total	GJ	% of total	GJ	% of total
Jan	8.7	1.3%	14.5	2.1%	7.9	1.2%	7.9	1.2%	7.9	1.2%
Feb	11.9	2.6%	24.2	5.4%	16.5	3.7%	16.5	3.7%	16.5	3.7%
Mar	19.9	6.4%	33.3	10.8%	28.4	9.2%	28.4	9.2%	28.4	9.2%
Apr	13.8	8.0%	20.6	11.9%	20.4	11.9%	20.4	11.9%	20.4	11.9%
May	4.6	19.2%	8.4	35.4%	10.4	43.5%	10.4	43.5%	10.4	43.5%
Oct	9.8	6.1%	16.3	10.1%	13.3	8.2%	13.3	8.2%	13.3	8.2%
Nov	11.3	3.1%	15.4	4.3%	10.9	3.0%	10.9	3.0%	10.9	3.0%
Dec	9.4	1.6%	13.1	2.3%	7.7	1.3%	7.7	1.3%	7.7	1.3%
Annual	89.2	3.3%	145.8	5.3%	115.4	4.2%	115.4	4.2%	115.4	4.2%

Table 3 Monthly Space Heating Load Met by Distributed Solar Thermal Storage Systems.

Full page