

Research Article

TECHNICAL, ECONOMIC, AND ENVIRONMENTAL ASSESSMENT OF HEATING SUPPLY APPROACHES FOR A RESIDENTIAL COMPLEX EQUIPPED WITH A DISTRICT HEATING SYSTEM IN KERMAN USING NATURAL GAS AND SOLAR ENERGY

Author: ¹Amir Hossein Mahdizadeh Farsangi*  ²Mohsen Saffaripour

¹M.Sc. Student in Mechanical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran.

²Assistant Professor, Department of Mechanical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

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CORRESPONDING AUTHOR

Amir Hossein Mahdizadeh
Farsangi

rezashams@gmail.com

<https://orcid.org/0009-0004-8057->

ABSTRACT

This study focuses on the modeling and design of a district heating system for a residential complex inspired by the Maskan Mehr housing project, where heating is currently provided by fossil fuels (natural gas). The complex comprises six blocks, each with nine residential units of 65, 75, and 85 m². An independent boiler system was modeled and designed to estimate both thermal and electrical energy demand. The research also explores the integration of solar energy with natural gas as a hybrid supply source for the district heating system. For each scenario, key performance indicators—including carbon dioxide emissions, total energy consumption, and associated costs—were assessed. Simulations were carried out using TRNSYS, DesignBuilder, and Valentin TSOL software.

The results show that annual space heating energy consumption is 51 kWh/m²·year for the independent boiler system, compared to 47 kWh/m²·year for the district heating system. Carbon dioxide emissions were calculated at 92,425 kg for the boiler system and 62,731 kg for the district heating system, highlighting the environmental benefits of district heating when supplemented with solar energy.

INTRODUCTION

Human energy consumption has a profound impact on the environment, affecting both people and other living organisms through energy production, utilization, and transmission. These impacts appear in the form of air pollution, increased waste generation, and the rise of greenhouse gas emissions ^[1]. Among these gases, carbon dioxide plays a particularly critical role, directly contributing to global warming and the accelerated melting of polar ice caps ^[2]. Heating and cooling of living spaces are among humanity's essential needs, and these demands are still largely met through fossil fuel consumption. This dependence on fossil fuels is one of the main drivers of increasing greenhouse gas emissions. Consequently, the transition to clean energy sources is not only a potential solution to energy supply challenges but also an effective strategy for reducing environmental pollution and emissions ^[3]. Since the early 1980s, significant efforts have been made to replace fossil fuels—such as oil, natural gas, and coal—with clean energy alternatives ^[4]. Today, more than 30% of global energy consumption is allocated to space heating, with residential buildings accounting for a substantial share of this demand ^[5]. District heating (DH) systems supply centralized heat through a network of pipelines to meet residential and commercial heating demands. The development of DH systems across different countries has been shaped by factors such as electricity, gas, and heat tariffs, energy regulations, market liberalization, and pollution taxes. The incorporation of combined heat and power (CHP) systems—where excess steam is utilized for district heating—has been shown to significantly enhance the overall efficiency of DH networks ^[6]. Numerous studies have investigated the integration of solar and geothermal energy for heating applications. Oergner et al. ^[7] (2005) analyzed a hybrid geothermal heat pump–solar system and identified significant compressor losses arising from electrical and mechanical inefficiencies, with the thermodynamic loss-to-investment ratio ranging from 0.035 to 1.125. Wong et al. ^[8] (2008) examined a system combining solar collectors with a geothermal heat pump and an underground storage tank, concluding that storage performance is highly dependent on solar radiation levels and collector surface area. Yang et al. ^[9] (2010) demonstrated that hybrid solar–geothermal systems can effectively provide heating during cold seasons through ground heat storage and cooling during warm seasons by lowering subsurface temperatures, achieving coefficients of performance (COP) between 4.5 and 6.5. Jesselson et al. ^[10] (2010) modeled a hybrid geothermal–solar system for a Swedish residential building using TRNSYS and found that electricity consumption decreased while the coefficient of performance (COP) during cooling seasons improved due to elevated soil temperatures. Bauer et al. ^[11] (2010) investigated central solar power plants with seasonal storage in Germany, concluding that both research advancements and operational experience contributed to improved technical performance, higher efficiency, and greater cost-effectiveness. Bakrsi et al. ^[12] (2011) conducted an experimental analysis of vertical geothermal heat pumps coupled with solar collectors, reporting pump COP values of 3.0–3.4 and overall system COP values of 2.7–3.0. Chen et al. ^[13] (2012) simulated a hybrid system for residential heating and domestic hot water, determining that a 44 kW heating demand could be met with a 40 m² solar collector and 264 m of borehole drilling. Yang et al. ^[14] (2012) analyzed a hybrid geothermal–solar system for an office building and reported up to a 30% reduction in electricity consumption, along with improved soil temperature stability during winter, which enhanced overall system performance. Di Gualafajra et al. ^[15] (2012) evaluated large-scale solar heating with seasonal storage under ten Spanish climate conditions, concluding that achieving a 50% solar fraction

could render these systems competitive with conventional residential boilers. Jiang Li et al.^[16] (2014) demonstrated in China that solar collectors contribute to increased soil temperatures, thereby reducing heat pump energy consumption, while storage tanks ensure stable and continuous heating supply. Andreou et al.^[17] (2016) emphasized that solar thermal plants integrated with underground storage and biomass support are well-suited for low- to medium-density regions in the Mediterranean. Toulos et al.^[18] (2016) carried out a multi-objective optimization of solar thermal plants with seasonal storage, demonstrating significant environmental and economic advantages over conventional gas heating. Kiampi et al.^[19] (2018) performed a thermodynamic and economic assessment of hybrid solar–geothermal district heating systems, reporting potential reductions in primary energy consumption and greenhouse gas emissions of 4–6%. Reed et al.^[20] (2018) evaluated solar district heating in the United States and found that systems incorporating underground storage represent competitive alternatives to natural gas–based residential heating. Building on these previous studies, the present research investigates the design and implementation of a district heating system for the Maskan Mehr housing project in Kerman. Using TRNSYS and DesignBuilder software, the study evaluates system costs and carbon emissions while determining the optimal capacities of solar and geothermal components to maximize both environmental and economic performance.

RESEARCH METHODOLOGY

The residential complex analyzed in this study consists of 54 units with a total usable area of 3,083 m², distributed across six building blocks. Each block has four floors, with the ground floor allocated for parking and residential units beginning from the second floor. The complex is modeled after Maskan Mehr apartments, and the architectural layouts of the units are based on standard designs from this housing scheme. Each unit includes a living room, kitchen, bedrooms, and bathrooms, with unit sizes of 65, 75, and 85 m². The study investigates the heating supply of the complex using two approaches: first, independent central boiler systems for each block, and second, a district heating system combining solar energy and natural gas. To achieve this, climate data and heating load parameters were collected according to relevant standards, and the buildings were modeled using appropriate simulation software. Heating systems were then designed in detail, and simulations were conducted to evaluate energy consumption, carbon dioxide emissions, and system costs. The district heating system was analyzed under two scenarios: (1) using natural gas boilers, and (2) a hybrid system using solar collectors alongside boilers. Each unit was assumed to house four occupants, with reduced presence between 8:00 and 14:00 to reflect typical working hours. Indoor thermal conditions were set according to ASHRAE standards, with clothing insulation values of 1 clo in winter and 0.5 clo in summer. The heating setpoint temperature was 21°C, with a setback at 18°C. Infiltration rates, window, and door specifications were defined based on standard tables and building codes. Fluorescent lighting was modeled, with power levels of 150 W and 480 W assigned to different areas, and daily hot water consumption was assumed to be 200 liters per unit. For the first approach (independent boilers), each block was equipped with its own boiler, pump, and radiator network, with each boiler serving nine units. Annual energy consumption and carbon emissions were calculated for this system. In the second approach (district heating), a single primary circuit supplies hot water to all radiators across the complex. Two scenarios were considered for heat supply: using either natural gas or solar energy. Component

specifications for boilers, pumps, and solar collectors were determined, and, due to the similarity of the building blocks, calculations were performed for one representative block. For the central boiler system, the primary and distribution networks, including radiators, were designed for each floor and unit. The heating load per block was estimated at 43 kW. Radiators were selected based on this load, using H500 Elna units with a capacity of 615 Btu/h, available in 3, 5, 7, and 10-fin configurations. The district heating system design was based on the total heating load of the entire complex. It consists of a primary circuit, including the boiler and pump, and a secondary distribution network delivering heat to the buildings. Figure 1 illustrates the schematic of this system.

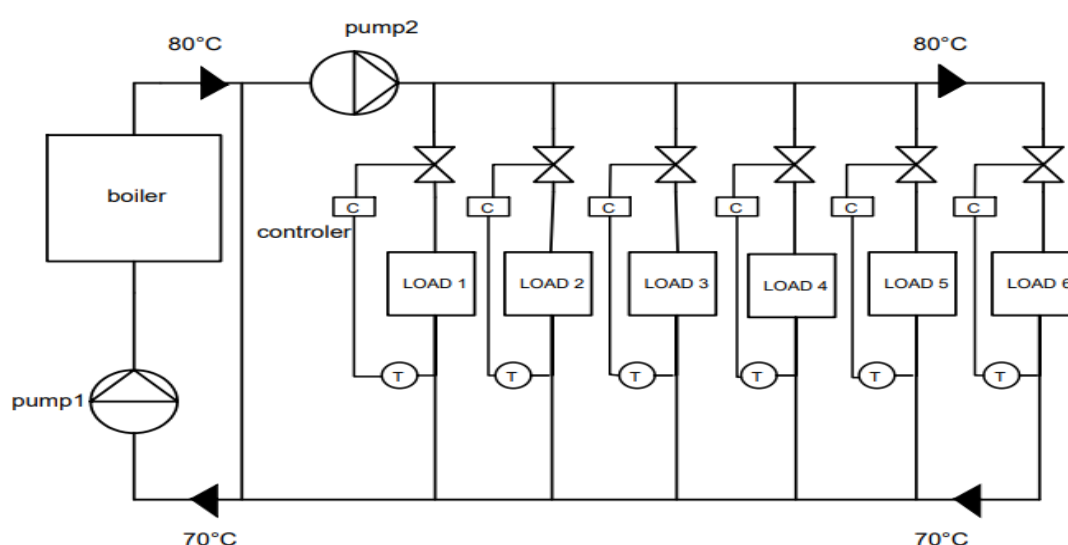


Figure 1: District Heating System Circuit

In this circuit, the heat source can operate under three scenarios: boiler, solar energy, or geothermal energy. Pump 1 operates at a constant speed, while Pump 2 functions with variable speed. Two-way valves are used to enable variable flow control through the pumps.

RESULTS

Building Heating Load

By specifying the building materials, heating system, number of occupants, lighting, and internal loads, the simulation calculates the daily design heating load. Additionally, the contribution of each building component to heat loss is determined.

Table 1: Contribution of Each Building Component to the Heating Load

Building components	Heat load share (kW)
Windows	-31.35
Exterior walls	-70.25

Interior ceiling	0.11
Floor	-38.43
Interior walls	-14.53
Exterior ceiling	-17.37

Central Boiler System

The components of the central boiler system are shown in Figure 2. The distribution network and radiator specifications were described in Chapter 3. The following section provides a detailed explanation of this system and specifies the characteristics of its other components.

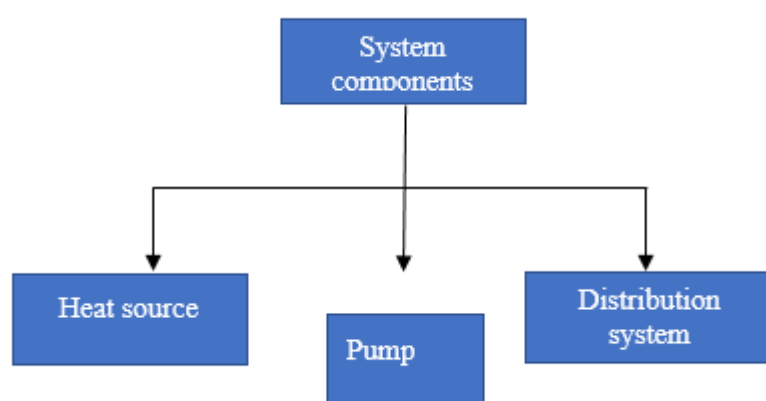


Figure 2: Components of the Boiler Room

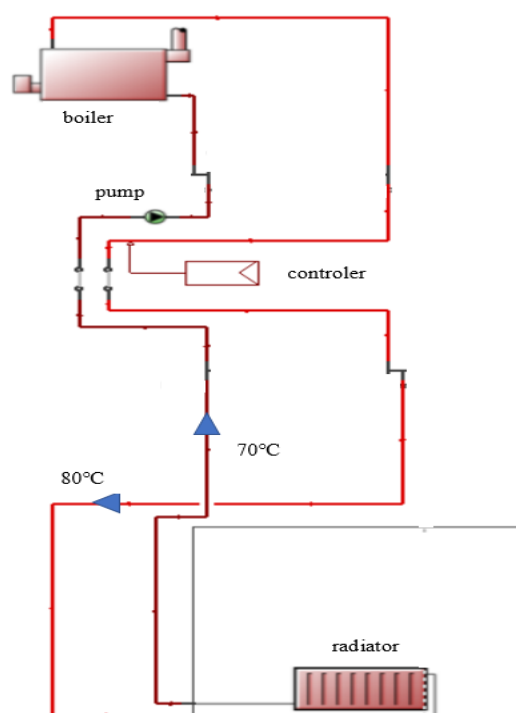


Figure 3: Schematic of the Independent Boiler System for Each Building Block

Schematic of the Central Boiler System

Each building block is equipped with its own independent heating system. In other words, each block has a dedicated boiler room, with the schematic following the layout shown above. Accordingly, the complex includes six boilers, each supplying hot water at 80°C to the radiators. After circulating through the distribution system and radiators on each floor, the water returns to the boiler at 70°C.

The building pumps operate at a constant speed, with their specifications—such as head and flow rate—determined based on the heating demand of each building. Since all building blocks are similar, the boiler capacity is designed to match the peak heating load of a single block. Considering a peak heating load of 45 kW per block, a 50 kW cast-iron boiler from Shofazkar is selected for each block.

Table 2: Specifications of the Central Boiler Room Boiler

Boiler specifications	
Number of boiler fins	5
Heating capacity (kW)	50
Chimney diameter (mm)	145
Boiler connection size (in)	0.5,1
Boiler length (mm)	565
Weight (kg)	315
Maximum operating pressure (bar)	4
Maximum operating temperature (°C)	105
Water pressure drop (mbar)	300

Based on the flow rate of each building block and the head loss calculated in the previous section, the appropriate pump for the building is selected. The chosen pump is the URD 104/5 model, with an efficiency of 70%, selected using the intelligent system provided by Pumpiran. Since the pump in the central boiler system operates at a fixed speed, its electricity consumption is calculated using the formula described in Chapter 3.

$$W = \frac{GPM \times TDH \times 0.746}{3960 \times \eta_{pump} \times \eta_{motor}} = \frac{302}{2494} = 0.121 \text{ kW}$$

Consequently, considering the entire heating season, the total electricity consumption of the pumps for the residential complex is 2,630 kWh.

The table below presents the simulated energy consumption, including the amount of gas used exclusively for space heating within the building.

Table 3: Monthly Gas Consumption for Building Heating

Consumption (m ³)	Consumption (kWh)	Date
5219	49059	2023.1.1
3763	35372	2023.2.1
1312	12339	2023.3.1
0	0	2023.4.1
0	0	2023.5.1
0	0	2023.6.1
0	0	2023.7.1
0	0	2023.8.1
0	0	2023.9.1
0	0	2023.10.1
1928	18124	2023.11.1
4597	43213	2023.12.1

Table 4 presents the simulated monthly carbon dioxide emissions over one year resulting from space heating using the boiler and gas system. These values account only for CO₂ emissions from space heating, while other sources, such as cooking or occupant activities, have been excluded.

Table 4: Monthly Carbon Dioxide Emissions from the Central Boiler System

Carbon dioxide emissions (kg)	date
9213	2023.1.1
6643	2023.2.1
2317	2023.3.1
0	2023.4.1
0	2023.5.1
0	2023.6.1
0	2023.7.1
0	2023.8.1
0	2023.9.1
0	2023.10.1
3404	2023.11.1
8116	2023.12.1

District Heating System

Natural Gas

The second scenario for building space heating involves the use of a district heating system. As shown in Figure 4, the components of this system include a heat source—which, in this scenario, is a boiler fueled by natural gas—a pump, and the distribution network, consisting of

pipings and radiators.

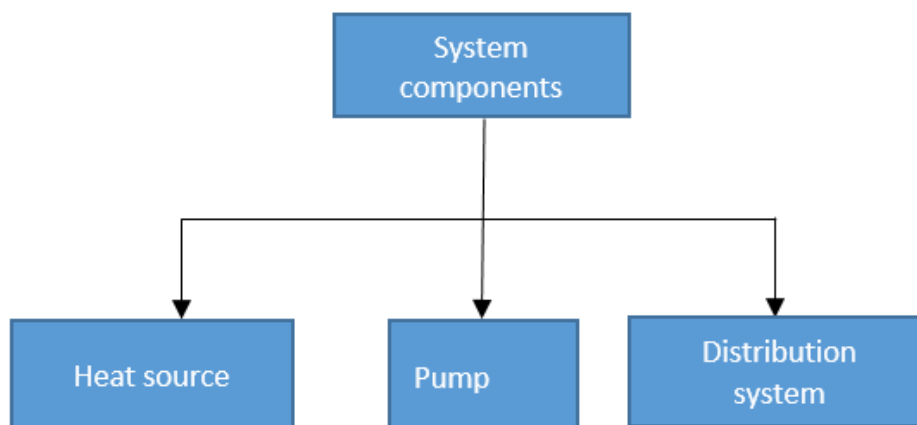


Figure 4: Components of the District Heating System

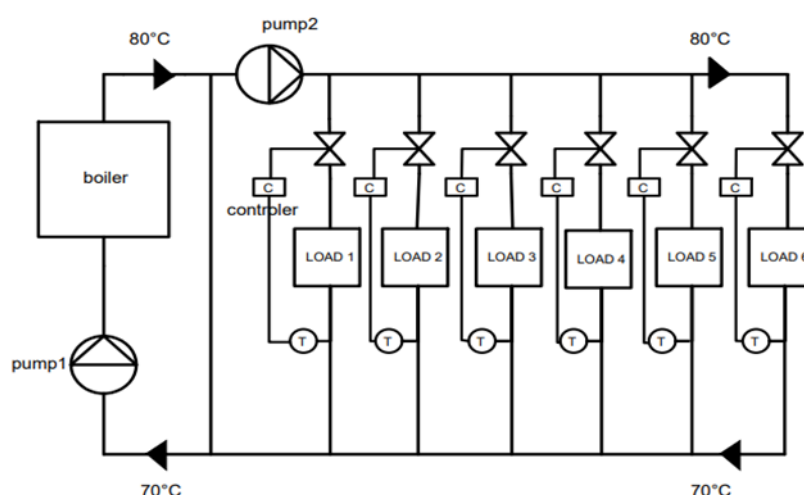


Figure 5: Schematic of the District Heating System Designed in DesignBuilder

Schematic of the District Heating System

According to the district heating system circuit described in Chapter 3, this system consists of two main sections: the primary circuit and the secondary circuit. The primary circuit includes the heat source (boiler) and a pump. In this section, hot water at 80°C is sent to the buildings, and the pump operates at a constant speed to ensure a continuous supply of hot water.

In the secondary circuit, each building draws water according to its specific heating demand, with the pump operating at a variable speed. After passing through the radiators and transferring heat to the building interior, the water returns to the primary circuit and boiler at 70°C. In the designed system, during peak load conditions, the return water temperature to the primary circuit is 70°C; under partial load, it ranges between 70°C and 80°C; and when the system is off or heating is not required, water returns at 80°C.

The selected boiler must meet the total heating demand of the buildings, which is 255 kW. A 300 kW boiler from Shofazkar has been chosen for this scenario. The specifications of the

boiler are presented in Table 5.

Table 5: Specifications of the District Heating Boiler (Scenario 1)

Boiler Specifications	
Number of boiler fins	5
Heating capacity (kW)	300
Chimney diameter (mm)	307
Boiler length (mm)	1503
Weight (kg)	651
Maximum working pressure (bar)	4
Maximum working temperature (°C)	105
Water pressure drop (mbar)	200

Pump **pump1** operates at a constant speed, while pump **pump2** is designed to operate at a variable speed to save energy. The flow rate of the pump was calculated based on the heating load of the buildings using the following equation:

$$Q = \frac{\text{load}(\frac{btu}{h})}{500 \times \Delta T(^{\circ}F)} \quad \frac{870060}{10000} = 87 \text{ gpm}$$

The head loss for **pump1** includes the losses in the boiler room, boiler, and collectors, which, according to the catalog, is 10 feet. The head loss for **pump2**, considering the distance to the buildings and the longest route to the farthest consumer, is 31 feet.

Using the Pumpiran system, **pump model EN 50-160** was selected, with an efficiency of 74.5% and a rotational speed of 985 rpm.

Table 6: Electricity Consumption of the Pumps

Electricity Consumption (kWh)	Pump
880	pump1
1075	pump2

Based on the simulation results, the district heating system prevents the emission of 48 kg of carbon dioxide, saves 79 kWh of thermal energy, and reduces electrical energy consumption by approximately 30% compared to the independent boiler system.

If the heating system were to rely entirely on renewable energy sources, the carbon dioxide emissions would be zero. During the simulation, the software accounted for some carbon dioxide emissions, which are not related to the heating system itself but arise from other factors such as occupant presence, cooking, and similar activities.

The resulting carbon dioxide emissions are presented in **Table 7**:

Table 7: Carbon Dioxide Emissions in the District Heating System (Scenario 1)

Amount of Carbon Dioxide Emissions (kg)	date
5617	2023.1.1
5068	2023.2.1
5601	2023.3.1
4887	2023.4.1
5043	2023.5.1
4887	2023.6.1
5051	2023.7.1
5043	2023.8.1
4887	2023.9.1
5606	2023.10.1
5420	2023.11.1
5616	2023.12.1

Solar Heating System

The second scenario for supplying energy to the district heating system involves the use of solar energy. The components of this system are illustrated in **Figure 6**.

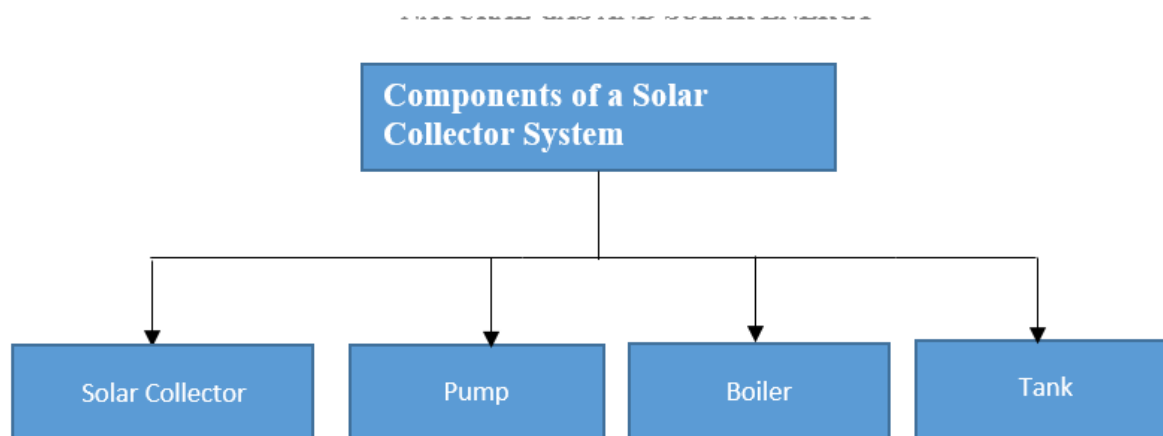


Figure 6: Components of the District Heating System

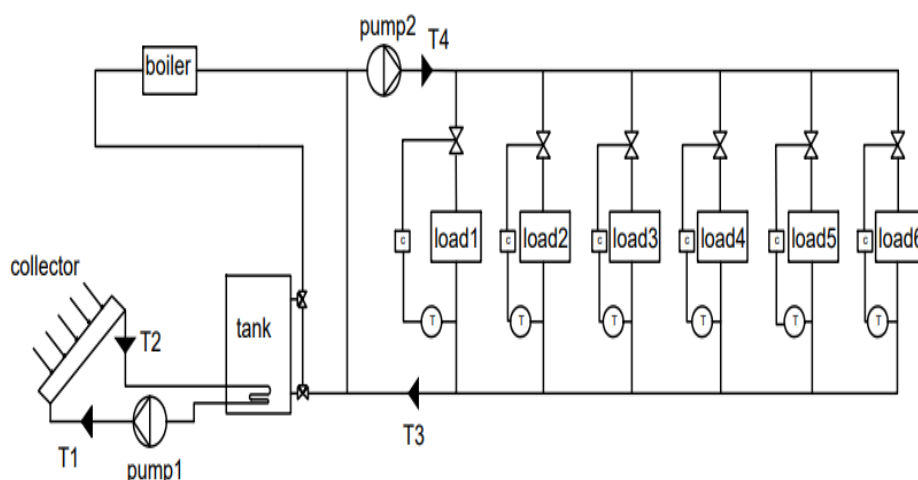


Figure 7: Schematic of the Solar Heating System

The system shown in Figure 7 consists of solar collectors, a storage tank, a boiler, and pumps. The water enters the collector at 70 °C and exits at 80 °C. After passing through the storage tank, the water flows into the boiler, which compensates for any temperature drop below the set point. The heated water at 80 °C is then delivered to the radiators, and after transferring heat to the building, the return water at 70 °C goes back to the collectors.

During sunny hours, the solar collectors provide the building's heating. During periods without sunlight, the boiler supplies the required heat. A three-way valve directs water from the storage tank to the boiler when solar energy is insufficient, ensuring the radiators receive water at 80 °C. The boiler's capacity is designed according to the peak heating load at 6:00 AM, which is 255 kW. The energy consumption of the boiler and collectors is summarized in Table 8 and illustrated in Figure 8.

In this system, water at 80 °C is delivered to the secondary circuit and radiators, while the return water at 70 °C flows back to the primary circuit. Under partial load conditions, the return water temperature ranges between 70 °C and 80 °C. When the system is not in use, the return water maintains 80 °C. During non-sunny hours, the three-way valve closes the path to the collectors and directs water to the boiler, while in sunny periods, water flows to the storage tank and collectors.

According to Figure 8, during the design day, temperatures T1 and T2 vary due to changes in tank temperature and solar radiation. Simulation results show that the average temperatures are 72.7 °C and 77.6 °C, respectively.

To achieve optimal performance of the collectors, the tilt angle must be set correctly. For domestic hot water, the optimal angle is 27.3°, whereas for space heating during the cold season, an angle of approximately 45° is recommended. Tables 8 and 9 present the collector specifications and the optimal tilt angles.

Table 8: Collector Specifications

Collector Specifications	
Number of Collectors	15 vacuum tubes, 58 × 1800 mm
Weight	70 kg
Operating Pressure	0.3 bar
Length	126 cm
Width	187 cm
Height	163 cm
Absorbing Area	2.2 m²
Water Pressure Drop	0.245 bar

The collector area required to supply the buildings' heating demand is 432 m².

Table 9: Optimal collector angles on a monthly, seasonal, and annual basis in Kerman

Month	Monthly Angle	Optimal	Seasonal Angle	Optimal	Annual Angle	Optimal
January	56.23		45.49		27.3	
February	47.65					
March	30.31					
April	14.11		2.93			
May	0					
June	0					
July	0		10.89			
August	7.94					
September	26.21					
October	42.88		55.45			
November	55.23					
December	59.24					

The present solar system includes a backup system to ensure hot water supply in case of unexpected issues. On cloudy or non-sunny days, the boiler provides the building's heating demand. This backup system is designed to meet the peak heating load, which is 255 kW. Figure (8) illustrates the boiler's monthly energy consumption in kWh.

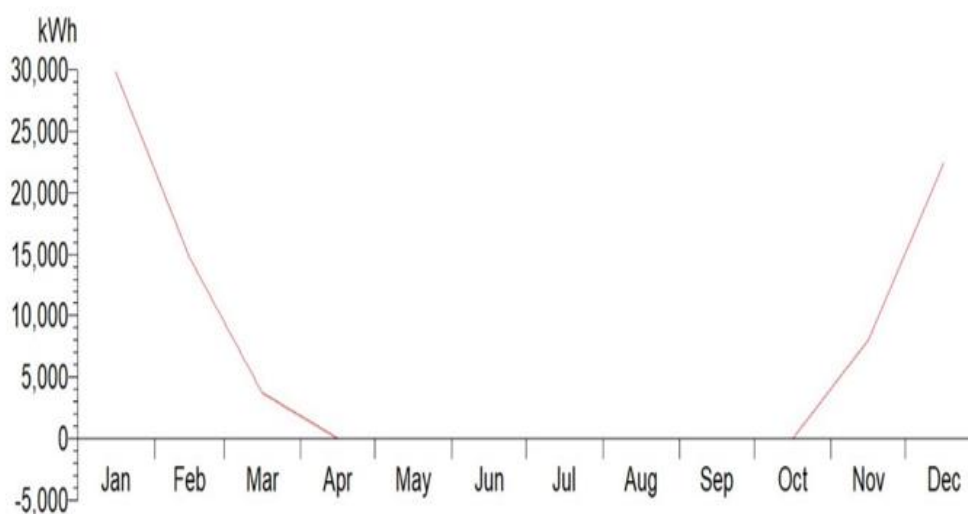


Figure 8: Boiler energy consumption in the solar system as simulated in TISOL software

After completing the simulation, the results are summarized in Table (10). According to the results, the combined boiler and solar energy system saves approximately 100,000 kWh of energy. Additionally, by reducing the boiler load and lowering fossil fuel (natural gas) consumption, it leads to a decrease of about 24,000 kg of carbon dioxide emissions.

Table 10: Specifications and parameters of the solar-based district heating system (Scenario 2)

Parameters	Values
Solar Fraction of the Entire System	56.3%
Energy Produced by the Collectors	101,741 kWh
Collector Area	432 m ²
Water Tank Volume for Space Heating	21 m ³
Amount of Carbon Emission Saved	24,294 kg
Energy Consumed by the Boiler	79,000 kWh

The efficiency of the collectors was also examined during the cold seasons. In these months, the maximum efficiency reached up to 35%, while the minimum efficiency was around 20%. In Table (11), the amount of energy and carbon dioxide saved by the solar and natural gas systems are compared.

Table 11: Comparison of Energy Consumption and Carbon Dioxide Emissions of the Systems

Carbon Dioxide Emission (kg)	Energy Amount (kWh)	
24,294	107,987	Solar Energy
48	79	Natural Gas

Economic Analysis of the System

Table 12 has been prepared based on equipment price inquiries from the market and various sources.

Table 12: Costs Related to Heating Systems

Equipment	Cost (Rial)
Solar Collector per Square Meter	65,000,000
Fixed Cost of Solar Collector	875,000,000
Boiler Cost for Central Boiler Room	60,000,000
Boiler Cost for District Heating System	830,000,000
District Heating Water Pump Cost (Scenario 1)	174,000,000
Water Pump Cost per Building	40,000,000
Solar Collector Water Pump Cost	45,000,000

Table 13: Assumptions for Economic Analysis

Parameters	Values
Dollar Exchange Rate	700,000
Project Lifetime	20 years
Maintenance Cost	1% of Total Initial Investment
Rate of Tariff Increase	15% per Year

Based on the cost calculations, the initial implementation cost of the solar heating system was determined to be 36,125,000,000 IRR, while the cost of the district heating system using natural gas was 1,143,000,000 IRR.

Table 14: Payback Period of the Solar Energy System

Heating System	Payback Period (Years)
Solar Energy System	15

CONCLUSION

Based on the simulations conducted in this study, it was determined that the district heating system consumes less energy. This is mainly because the district heating system eliminates the need for multiple boilers and other components. By implementing a district heating system and adopting renewable energy sources, it is possible to prevent the annual emission of 29,694 kilograms of carbon dioxide. Additionally, district heating systems can contribute to national revenue and exports, as switching to renewable energy can save 15,810 cubic meters of natural gas annually.

Considering these results, it is recommended to conduct multi-objective optimization of a combined geothermal heat pump system with solar collectors, evaluate the performance of this combined system under various climatic conditions, and optimize a hybrid heating system integrating a geothermal heat pump, solar collectors, and natural gas using different optimization methods for comparison.

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