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Parametric analysis for the determination of solar collector and hot water tank capacity in solar-assisted heating systems

Ersin Haydaraslan *1

[1]Recep Tayyip Erdoğan University, Department of Electricity and Energy, 53100, Rize, Türkiye

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Abstract: In this study, a study was carried out on integrating solar assisted systems into heating systems in a building. For the study, an existing building was modeled with the DesignBuilder building energy simulation program. The scenarios were created on the model to determine the number of solar collectors and the capacity of the water tank used in solar assisted heating systems. The primary energy consumption, global costs and payback periods of the scenarios created were obtained by parametric analysis. According to the results obtained, the solution that reduces primary energy consumption the most is SYS20, the solution that reduces the global cost the most is SYS1 and the optimum solution is SYS7. Considering the payback periods, SYS1 was determined as the most appropriate solution to be applied in the study since it was the solution with the minimum payback period. At the end of the study, it was seen that primary energy savings could be reduced by up to 47% with solar energy assisted heating system. Thanks to the study, a reference source for the number of solar collectors and water tank capacity selection in Isparta and provinces with similar climates has been created.

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Güneş enerjisi destekli ısıtma sistemlerinde güneş kolektörü ve sıcak su deposu kapasitesi seçimi için parametrik analiz

Anahtar Kelimeler
Enerji
Güneş enerjisi
Isıtma sistemi
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Öz: Bu çalışmada konutlarda ısıtma sistemlerine güneş enerjili destek sistemlerinin entegre edilmesi ile ilgili bir çalışma yapılmıştır. Çalışma için mevcut bir bina DesignBuilder bina enerji simülasyon programı ile modellenmiştir. Model üzerinde ısıtma sistemine entegre edilecek en uygun güneş kolektörü sayısı ve sıcak su deposu kapasitesinin belirlenmesi için senaryolar oluşturulmuştur. Oluşturulan senaryoların birincil enerji tüketimleri, global maliyetleri ve geri ödeme süreleri parametrik analiz ile elde edilmiştir. Elde edilen sonuçlara göre birincil enerji tüketimini en çok düşüren çözüm SYS20, global maliyeti en çok düşüren çözüm SYS1 ve optimum çözüm ise SYS7 olmuştur. Geri ödeme süreleri göz önüne alındığında ise SYS1 en kısa geri ödeme süresine sahip çözüm olduğu için çalışmada uygulanabilecek en uygun çözüm olarak belirlenmiştir. Çalışma sonunda ısıtma sistemlerine güneş enerjisi desteğiyle %47'ye varan birincil enerji tasarrufu elde edilebileceği görülmüştür. Çalışma ile Isparta ve benzeri iklime sahip illerde güneş kolektörü sayısı ve su tankı kapasite seçimi referans bir kaynak oluşturulmuştur.

1. Introduction

Buildings have a large share of the total energy consumption. The energy consumption in the building is supplied with fossil fuels, which consumed in the near future. Therefore, in building design, some parameters should be considered to reduce the energy demands of the building [1]. There are two important parameters to reduce energy consumption in buildings: building envelope and

* İlgili yazar/Corresponding author: haydaraslanersin@gmail.com.

system equipment (heating, cooling, and hot water supply (DHW) systems) [2-3]. While energy consumption can be reduced by the appropriate selection of system equipment used in buildings, it can also contribute to reducing the total energy consumption by providing some of the energy demand in these systems with renewable energy instead of fossil sources. Within the scope of this knowledge, a study was carried out on integrating solar assistant systems into standard heating systems in residential buildings.

Many studies were carried out on the use of solar energy system to reduce the energy consumption in buildings. Lerch et al. (2015) compared a serial and parallel connection of solar assisted heating system for a single-family house. In the study, six different systems were designed: a reference system without a solar collector and an interconnected system by five different connection types that had two different collector areas (14 and 30 m^2). It was concluded that the system performance of the non-solar assisted heating system increased with the use of solar energy. Moreover, it was also found that serial connected heating system with the 14 m^2 collector area was the most efficient system [4]. Mustafaraj et al. (2014) numerically examined the effect of heating systems with solar assisted on building energy performance. In the study, it concluded that, monthly heating energy saving potential changes from 20% to 27% with solar assisted heating system compared to conventional heating system [5]. Kalfa et al. (2018) carried out a numerical analysis to reduce the energy consumption of a building. In the study, solar assisted heat pump was used for heating, and compression the primary energy consumption between conventional heat pump and solar assistant one. As a result, it was concluded that the solar assisted heating system consumed approximately 12% less energy than non-solar assisted [6]. Ge et al. (2022) proposed to determine the optimal configuration of a solar assisted natural gas distributed energy system in their study. In the study, three scenarios were designed with the different structural solar assisted energy systems. The results of the study that the solar assisted energy system has between 2.90% and 7.48% less annual total cost than the conventional energy system [7]. Jia et al. (2022) in a study, they integrated the solar energy with the combined heat and power generation system. In the study, there were lots of parameters to decrease energy demands. One of these parameters was the solar to fossil fuel input ratio of the system. As a result of the study, the solar assisted system could achieve an annual fuel saving efficiency average of 50.82 %. Also it was conducted that as the solar-to-fuel input ratio increased the fuel savings was as high as 72.60 %, and the energy savings was as high as 39.72 % [8]. Li et al. (2023) proposed the concept of air source heat pump assisted solar energy for a building. The study was carried out experimentally and numerical to discover the technical and economic performances of solar assisted heating system. The results show that the heat pump assisted solar energy system improves technical and economic performance in comparison with non-solar assisted heat pump. Also, it is concluded that the primary energy saving rate of the solar assisted system was 66.4 % compared the traditional heat pump [9]. Yang et al. (2023) reported the numerical simulations of solar assisted air source heat pump heating systems that integrate solar collectors for domestic heating. In the study most important parameter was the collector size which was changed from 6 m^2 to 18 m^2. The other one was the collector type of concentrated solar collector, flat plate solar collector and compound parabolic concentrator solar collectors. As a result of the study, for the same seasonal performance, the size of the concentrated solar collector required is 12 m^2 whereas the size of the flat plate solar collector required is 18 m^2 for the studied building. The results also showed the potential to further reduce the size of the concentrated solar collector to 9 m^2 or less. At the end of the study, it was reached that as the collector size decreased, the payback time decreased, while the energy consumption increased. For this reason, it was stated that the optimum collector size selection was important [10].

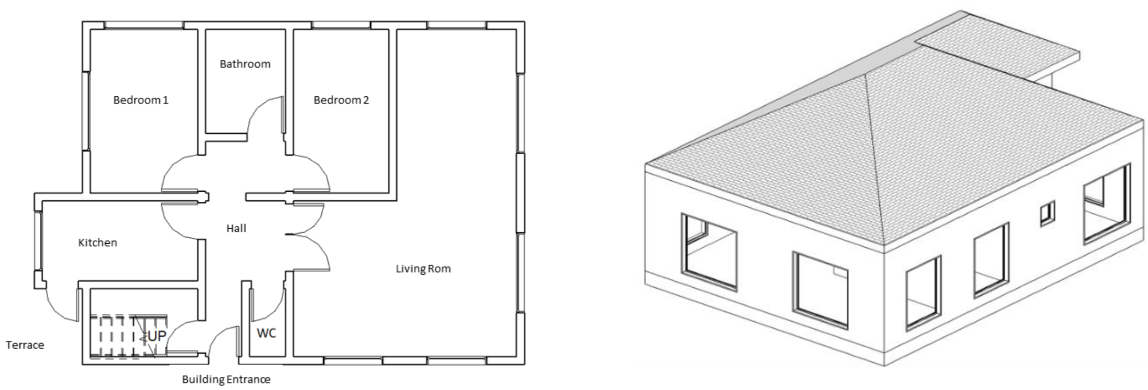
In this study, it was examined that changes of the energy performance with the integrating solar assistant into the heating systems in residential buildings. A parametric analysis was carried out to determine the number of solar collectors and the capacity of the hot water tank used in solar assisted heating systems. The novelty of the study is that it is a reference source for solar collector and water tank capacity selection for solar assisted heating systems in Isparta and cities with similar climates.

2. Materials and Methods

An existing detached building was modeled and simulated by using the building energy simulation program DesignBuilder. A reference model was established by defining the building construction, heating, and hot water system. After the reference model was established, new alternative system was developed on these models. The annual primary energy consumption and global costs of reference and other systems were obtained and compared. According to the findings, monthly energy consumption values were analyzed for a reference and three selected system. In addition, the payback periods of alternative systems were also examined. The province of Isparta from the Mediterranean region was chosen as the study region,

Table 1. Climatic data of Isparta

	January	February	March	April	May	June	July	August	September	October	November	December	ANNUAL
Avg.Temperature (°C)	1.8	2.9	6.0	10.8	15.5	20.0	23.5	23.2	18.7	13.1	7.6	3.5	12.2
Avg.Max.Temp. (°C)	6.2	7.7	11.6	16.7	21.8	26.5	30.3	30.6	26.4	20.5	13.9	8.1	18.4
Avg.Min.Temp. (°C)	-2.0	-1.2	0.9	4.8	8.6	12.3	15.3	15.1	10.9	6.7	2.6	-0.3	6.1
Avg. Sunshine Duration (h)	3.8	4.7	5.7	6.8	8.3	10.3	11.2	10.7	9.4	7.0	5.3	3.3	86.5
Max. Temperature (°C)	17.6	22.5	26.8	29.5	33.0	36.2	42.3	41.2	37.1	32.2	25.4	20.0	42.3
Min. Temperature (°C)	-19.2	-21.0	-18.5	-7.7	-1.2	4.3	4.9	7.0	-0.8	-4.2	-11.5	-15.4	-21.0



(a) (b)

Figure 1. (a) Floor plan, (b) building perspective view

due to the cold winter months and the long sunshine time (Table 1) [11].

2.1. Building Geometry

An existing, single-storey building was chosen for the study. Three people live in the building that consists of seven thermal zones. Total occupancy area is 92 m^2. The perspective view and the floor plan are shown in the Figure 1.

2.2. Mathematical Model

The primary energy consumption and global cost calculation of the building was performed for investigating performance of solar assisted heating system [12]. General equations for primary energy consumption and global cost;

$$PEC = \sum (\dot{Q}_{consumption} \; x \; K) \quad (1)$$

$$Cg(\tau) = CIn + \sum_j \left[\sum_i^{\tau} \big(Cy(\tau) + Cr(\tau)\big) - Vf, \tau(j) \right] \quad (2)$$

The details of these equations were detailed our previous work [13]. In global cost calculation, market interest rate (0.1765) and inflation rate (0.1114) were used by averaging long-term data [14]. The calculation period was defined as twenty years because of the system equipment life.

2.3. Numerical Simulation

The equations given in the previous section were solved simultaneously using the building energy simulation program. The details of building materials such as walls, floors, windows, and roofs used in the study are defined according to the values specified in TS 825 [15]. The construction information, indoor temperatures, occupancy profile, etc. information can be seen in the Table 2 [15, 16, 17]. On the other hand, the cooling is not covered in this study.

In the existing building, heating is provided by a gas fired boiler. The radiators are used for the heating system indoor units. The radiator capacities used for operation can be seen in the Table 3 [18]. With this information, the mechanical system of the reference system was established.

Table 2. Building characteristics

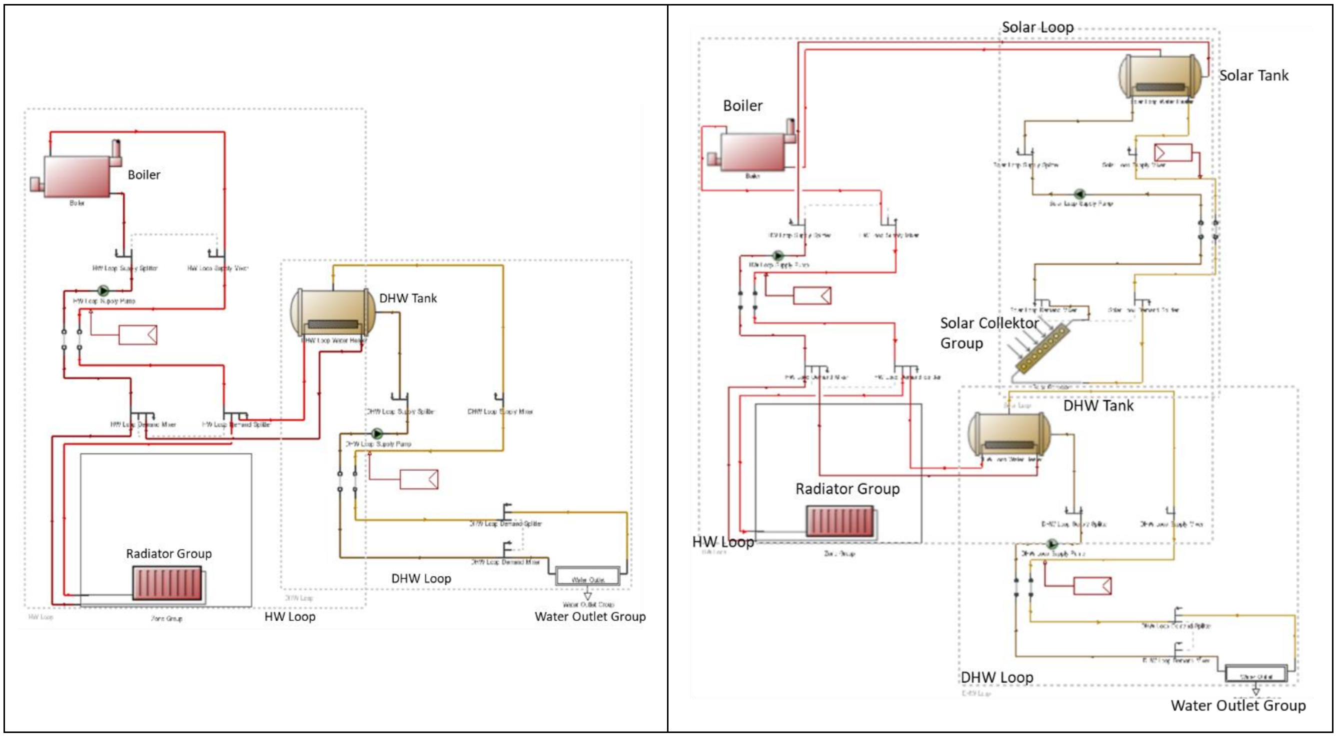
Main buildings dimensions					
Gross Length (N-S direction)	8.4 m		Gross Floor Area	91.91 m²	
Gross Length (W-E direction)	10.9 m		Gross Volume	248.15 m³	
Gross Height	2.7 m (1 floors)		Gross Roof Area	119.30 m²	
Building geometry-residential					
	Total	North	East	South	West
Gross Wall Area (m²)	135.82	36.60	36.30	26.33	43.56
Window Area (m²)	28.98	9.52	5.74	6.41	9
Window-Wall Ratio (%)	21.34	26.23	15.81	24.32	20.66
Weather Data	ASHRAE Isparta IWEC		Number of zones	7 Thermal zones	
Environmental control					
	Heating (°C)	Heating set back (°C)	Cooling (°C)	Cooling set back (°C)	
Living Room	20	18	-	-	
Kitchen	20	18	-	-	
Hall	15	13	-	-	
Bedroom 1-2	20	18	-	-	
Bathroom	24	22	-	-	
Occupancy Profile					
Weekdays	Unoccupied between 08.00-17.00		Weekend	Occupied all time	
Construction					
U_{wall}	0.612 W/m²K		$U_{floor\ on\ the\ ground}$	1.932 W/m²K	
$U_{ceeling\ (semi\text{-}exposed)}$	2.654 W/m²K		$U_{windows}$	2.673 W/m²K	
$U_{partition}$	1.665 W/m²K		Infiltration	0.8 ac/h	

Table 3. The radiator capacities by room

	Heating Capacity (W)
Kitchen	1798
Hall	1079
Living Room	6473
Bedroom 1	2158
Bedroom 2	1798
Bathroom	1438

The reference system consisted of two loop: the hot water (HW) loop and the domestic hot water (DHW) loop. The gas fired condensing boiler was used as the energy source for HW and DHW loop (Figure 2a). In addition to the reference system, solar assisted heating system was added to alternative systems (Figure 2b). The solar hot water produce system (solar loop) was installed not only to produce domestic hot water, but also to support space heating. The solar loop obtained its energy from thermal solar collectors. The water returning from the radiators was firstly taken to the solar loop system and then to the boiler. If the water temperature obtained by solar energy was not sufficient, it was heated up to the desired level with the boiler.

The mechanical system information such as the boiler [19], water tank [20] and pump capacity [21] of the reference and alternative system models are given in Table 4. The boiler and domestic hot water information was the same with reference system. But, the extra water tank, pump and new thermal solar collector was added for solar loop. The water thank capacity and thermal solar collector area were variable for all alternative system. The system code and the variable properties of alternative systems are given in Table 5. The collector area changed from 10 to 40 m² and tank volume from 200 to 2000 liters.



(a) (b)

Figure 2. The heating and hot water system scheme for (a) the reference model (b) for the alternative models

Table 4. Technical specifications of devices used in the reference and alternative systems

Reference	Heating: Radiator + Boiler (Gas) ; DHW: Boiler (Gas)					
	Nominal Capacity	**Nominal Efficiency**	**Design Loop Exit Temperature**		**Loop Design Temperature Difference**	
Boiler	24 kW	0.89	75 °C		10 °C	
Water tank	**Services**	**Tank Volume**	**Design Loop Exit Temperature**		**Loop Design Temperature Difference**	
	DHW loop	0.06 m³	56 °C		5 °C	
Pump	**Services**	**Type**	**Head**	**Water Flow**		**Electric Power**
	DHW loop	Variable speed	1 m (maks.)	0.5 m³/h (maks.)		7 W (maks.)
	HW loop	Variable speed	6 m (maks.)	2 m³/h (maks.)		70 W (maks.)
Alternative Systems	Heating: Radiator + Solar Assisted Boiler (Gas+ Solar) ; DHW: Solar Assisted Boiler (Gas+ Solar)					
	Nominal Capacity	**Nominal Efficiency**	**Design Loop Exit Temperature**		**Loop Design Temperature Difference**	
Boiler	24 kW	0.89	75 °C		10 °C	
Water tank	**Services**	**Tank Volume**	**Design Loop Exit Temperature**		**Loop Design Temperature Difference**	
	DHW loop	0.06 m³	56 °C		5 °C	
	Solar loop	Variable	Variable		Variable	
Pump	**Services**	**Type**	**Head**	**Water Flow**		**Electric Power**
	DHW loop	Variable speed	1 m (maks.)	0.5 m³/h (maks.)		7 W (maks.)
	HW loop	Variable speed	6 m (maks.)	2 m³/h (maks.)		70 W (maks.)
	Solar loop	Variable	1 m (maks.)	0.5 m³/h (maks.)		7 W (maks.)
	Area	**Efficiency**	**Slope**			
Thermal Solar Collec.	Variable	0.74 (maks)	Equal to latitude (37°)			

Table 5. The system code and the variable properties of alternative systems

CODE	Area (m^2)	Tank Volume (m^3)	CODE	Area (m^2)	Tank Volume (m^3)
SYS1	10	0.2	SYS11	30	0.2
SYS2	10	0.4	SYS12	30	0.4
SYS3	10	0.8	SYS13	30	0.8
SYS4	10	1.0	SYS14	30	1.0
SYS5	10	2.0	SYS15	30	2.0
SYS6	20	0.2	SYS16	40	0.2
SYS7	20	0.4	SYS17	40	0.4
SYS8	20	0.8	SYS18	40	0.8
SYS9	20	1.0	SYS19	40	1.0
SYS10	20	2.0	SYS20	40	2.0

3. Results and Discussion

The building's primary energy consumption and twenty-year global cost were calculated for the reference and other systems. The results obtained are seen in the Figure 3.

For the reference and other systems, the building's primary energy consumption and global cost were calculated as the result. On the Figure 3, each point represents the global cost and primary energy consumption of a system. The rightmost dot represented the reference system. The leftmost one was the SYS20 had the lowest primary energy consumption. In the bottom dot was SYS1 which had the lowest global cost. The optimum solution in terms of global cost and primary energy consumption was SYS7. So, for the study, if the nZEB building was desired, global cost could be ignored and SYS20 was appropriate. If the cost-optimized system was desired, SYS1 with the lowest global cost could be chosen. The energy consumption for monthly of Reference, SYS1, SYS7 and SYS20 are given in the Figure 4.

In the reference system, the energy was not consumed for heating between May and October, but it was consumed to produce hot water. In SYS1, energy was not consumed for heating and hot water during these months. On the other hand, between January-May and October-December, energy consumption for heating and hot water production decreased by approximately 13% compared to the reference system, thanks to the solar assisted heating system. This rate became 18% in SYS7 and %25 in SYS20. These rates were between 20% and 27% in the study by Mustafaraj et al [5]. When the primary energy consumption saving rates were examined; it was 12% in the study of Kalfa et al. [6] and it reached up to 66.4% in the study of Li et al [9]. In this study, the rates changed from 35% to 47%. When the results of the study were compared with the literature, it was seen that the results were compatible.

In SYS1 and SYS7, the energy was consumed to produce heating and hot water in October, while in SYS20 solar energy support was sufficient and energy was not consumed. Finally, the investment cost, annual cash flow and payback period of all systems are given in Table 6.

When the payback periods of all systems were examined, it was seen that the payback period of SYS10, SYS15, SYS17, SYS18, SYS19 and SYS20 was higher than the system lifetime. For other systems it ranged from 7.5 years to 17 years. It was seen that the payback period of SYS1, which has the lowest global cost, was 7.5 years. Since the building was not intended to be nZEB and as the payback period was the least solution, it could be said that SYS1 was the most appropriate system to be selected at the end of the study.

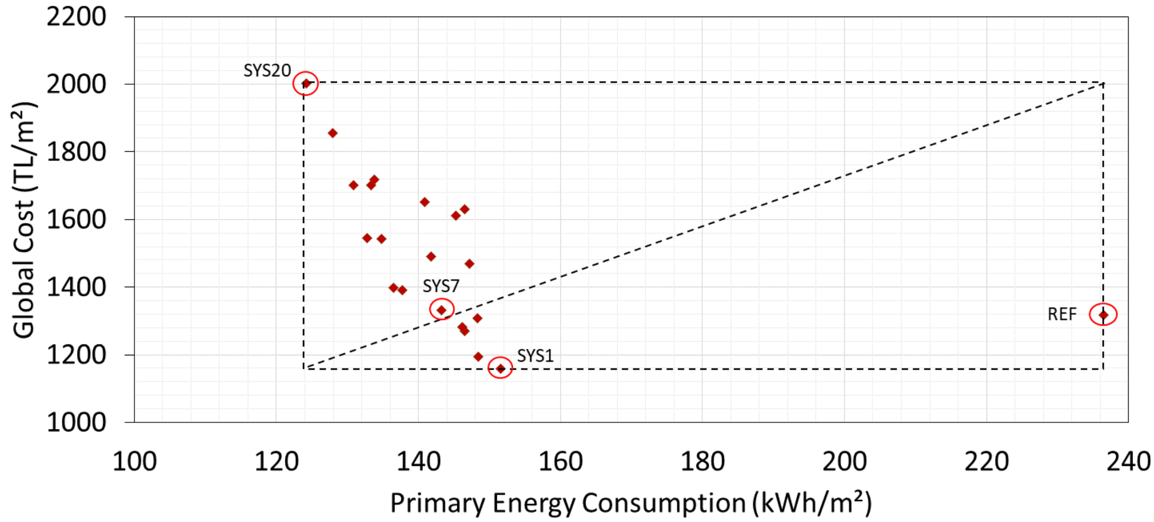


Figure 3. The primary energy consumption and global cost of all systems

Table 6. The investment cost, annual cash flow and payback period of all systems

	Reference	Investment Cost	Annual Cost	Annual Cash Flow	Payback Period
	TL/m2	TL/m2	TL/m2	TL/m2	Year
SYS1	113.62	280.85	76.26	37.36	7.5
SYS2	113.62	332.39	74.91	38.72	8.6
SYS3	113.62	421.92	74.08	39.55	10.7
SYS4	113.62	434.40	73.91	39.72	10.9
SYS5	113.62	777.57	73.52	40.11	19.4
SYS6	113.62	450.79	74.85	38.77	11.6
SYS7	113.62	502.33	72.61	41.01	12.2
SYS8	113.62	591.86	70.22	43.40	13.6
SYS9	113.62	604.34	69.65	43.97	13.7
SYS10	113.62	947.51	68.45	45.18	21.0
SYS11	113.62	620.73	74.38	39.24	15.8
SYS12	113.62	672.27	71.99	41.64	16.1
SYS13	113.62	761.80	68.94	44.68	17.0
SYS14	113.62	774.28	68.02	45.61	17.0
SYS15	113.62	1117.45	65.91	47.71	23.4
SYS16	113.62	790.67	74.09	39.54	20.0
SYS17	113.62	842.21	71.62	42.01	20.1
SYS18	113.62	931.73	68.30	45.33	20.6
SYS19	113.62	944.22	67.17	46.45	20.3
SYS20	113.62	1287.39	64.27	49.35	26.1

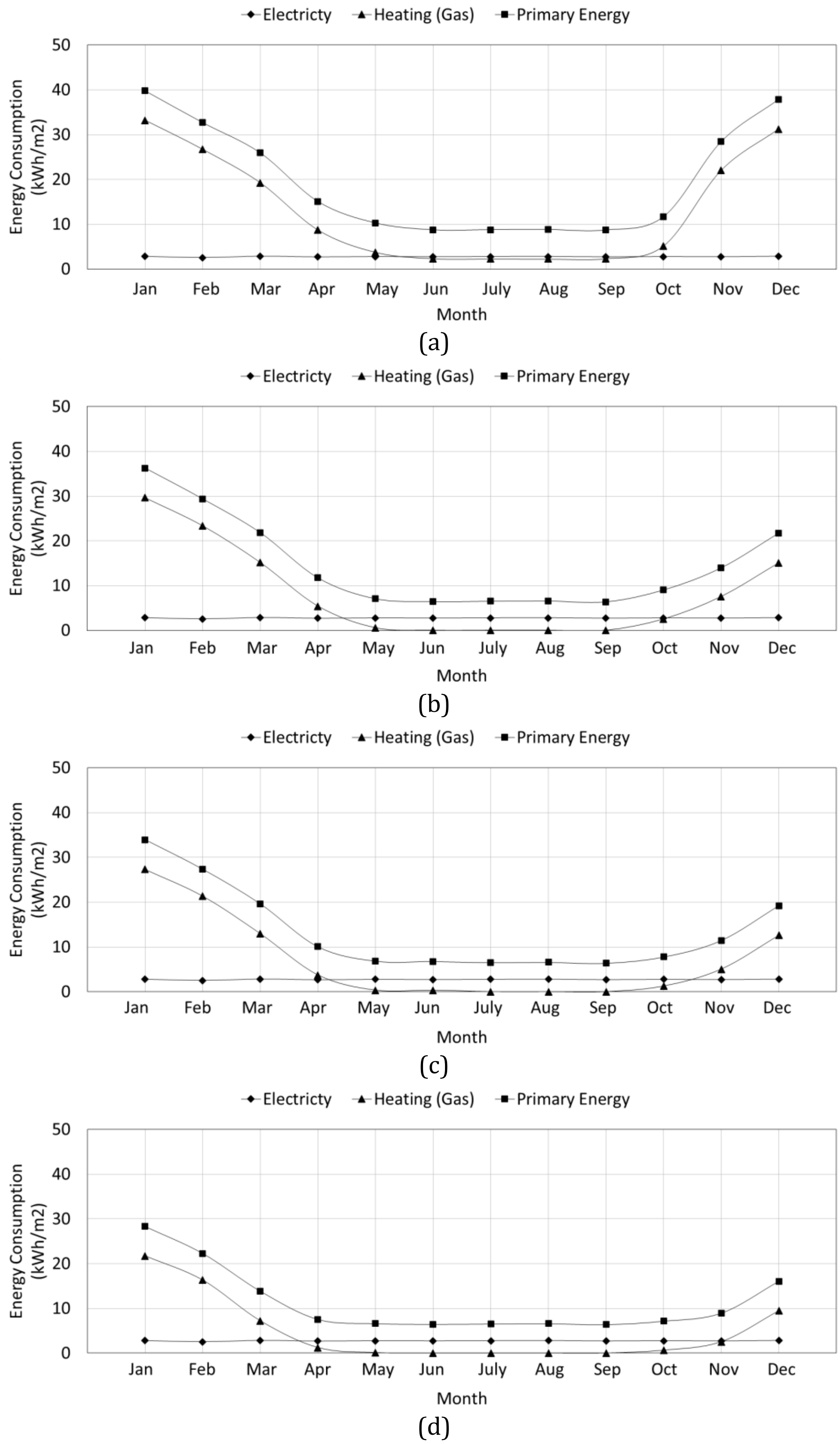


Figure 4. The energy consumption for monthly of (a) Reference, (b) SYS1, (c) SYS7 and (d) SYS20

4. Conclusions

This paper reports a numerical study to examine the effect of solar assisted heating system on the primary energy consumption of an existing building. The main conclusions are as follows:

- The solution that reduced primary energy consumption most was SYS20, but on the other hand this solution had the highest global cost. SYS1 was the solution that reduced global cost the most. The optimum solution in terms of global cost and primary energy consumption was SYS7.

- The primary energy consumption was reduced from 35% to 47% according to the different solutions. These rates were found to be consistent with other studies reviewed in the literature.

- The payback period of SYS10, SYS15, SYS17, SYS18, SYS19 and SYS20 was higher than the system lifetime. For other systems, it ranged from 7.5 years to 17 years.

- Since the payback period of this system is 7.5 years, SYS1 was the most suitable system at the end of the study.

As a result, it has been seen that energy consumption in existing or new buildings can be reduced by changes that can be made in the heating and domestic hot water production systems.

Nomenclature

PEC	: Primary energy consumption (kWh)
$\dot{Q}_{consumption}$	: Energy consumption for heating, cooling, and electricity needs (kWh)
K	: Coefficient depending on the source of the consumed energy
$Cg(\tau)$	: Global cost (TL/calculation period)
CIn	: Investment cost (TL)
$Cy(\tau)$	: Annual Cost (TL/annual)
$Cr(\tau)$	: Operation Cost (TL/annual)
$Vf,\tau(j)$	: Componen scrap value (TL).

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