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# Farklı Bina Isıtma Sistemlerinin Ekserjetik Performans Değerlendirmesi

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**Anahtar Kelimeler:**
Bina, ısıtma sistemi, sürdürülebilirlik, ekserji analizi, performans, ekserji

**Öne Çıkanlar:**

- Isıtma sistemi alternatiflerinin bina enerji performansına etkisi
- Bina performansı üzerinde konumun ve yerel bina standardının etkisi
- Binaların enerji ve ekserji verimliliği, sürdürülebilirlik endeksi ve esneklik oranı

**Makale Bilgileri:**
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**Amaç**

Çalışmanın amacı, enerji ve ekserjinin birincil enerji kaynaklarından aktığı her adımda ele alınan LowEx yaklaşımı ile İzmir ve Paris'te bulunan bir bina için bileşenlerin verimsizliğini ve aralarındaki ilişkileri ortaya çıkarmaktır.

**Materyal ve Metot**

Çalışmada incelenen bina olan Uşakizade Konağı, 4 yatak odası, 4 oda ve bodrum katı bulunan üç katlı tarihi bir villadır. Bu çalışmada, her ülkenin bina kodlarına uygun bina modeli oluşturmada Türkiye için TSE 825 ve Fransa için Termal Yönetmelik RT 2012 kullanılmıştır. Her iki şehir için altı farklı ısıtma sistemi seçeneği alternatifi incelenmiştir. İzmir ve Paris şehirlerinin meteorolojik verileri Meteonorm yazılımından alınmıştır. İç hava sıcaklığı 21 °C, %99,6 frekanslı kış tasarımı dış sıcaklıkları İzmir için -2,5 °C ve Paris için -3.1 °C olarak kabul edilmiştir. Her iki şehirde de binanın dış ortamla ilgili güneş ısı kazancı metrekare başına düşen güneş ışınımıdır. Hesaplamalarda temel olarak Schmidt yöntemi kullanılmıştır.

**Araştırma Bulguları**

Binanın özgül ve toplam ısı talep oranı İzmir için sırasıyla 27.09 W/m$^2$ ve 17.771 W olarak hesaplanmıştır. Fransa'da yürürlükte olan ve daha katı yalıtım standartları nedeniyle, Paris örneğinin özgül ve toplam ısı talebi oranının sırasıyla 12.49 W/m$^2$ ve 8.196 W olduğunu hesaplanmıştır. Farklı senaryolar için İzmir için %24.1 – 46.2 ve Paris için %22.4 – 40.3 arasında enerji verimliliği gözlemlenmektedir.

**Sonuç**

- İzmir'de toplam bina enerji talebi, minimum ve maksimum birincil enerji oranları Paris'in yaklaşık iki katıdır.
- Elektrikli kazan, en yüksek birincil enerji kullanımı sonucunu vermektedir.
- Güneş kolektörü, her iki şehir için en düşük ekserji talep oranları ve en yüksek toplam enerji verimliliği ile her iki şehir için de en iyi seçenektir.
- Birincil enerji dönüşümünde meydana gelen kazan ekserji kaybı oranı her iki şehir için de en yüksektir.

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# Exergetic Performance Assessment of Different Building Heating Systems

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**Highlights:**

- Effect of heating system alternatives on building energy performance
- Effect of location and local building standard on building performance
- Energy and exergy efficiency, sustainability index and flexibility ratio of buildings

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**Abstract:**
Exergy is an energy quality measure used to determine the sustainability of a system and its efficiency. The low exergy (Lowex) approach is useful to get sustainability goal in building sector. The energy and exergy flow from primary energy source to the building envelope from the are determined by this approach which is beneficial for improving energy and exergy use at all stages of the heating system in a building. In this study, a comparative evaluation of the energy and exergy performances of the different heating system alternatives for a three storey building, which has the same architectural features but is considered to be in Izmir and Paris, was made by the help of Lowex approach. The considered six heating system options are bio-mass/wood, a standard boiler, an electric boiler, a solar thermal collector, a ground source heat pump, and an air source heat pump. Various indicators such as energy and exergy efficiency, sustainability index and flexibility ratio are used in analyses and evaluations. In terms of total energy and exergy efficiency, it has been seen that the solar collector heating system alternative is the best option for both cities.

**Key words:** Building, heating system, sustainability, exergy analysis, performance, exergy

## 1. Introduction

Globally, around 32% of total final energy consumption comes from the building sector [1]. Energy in buildings is mainly consumed for the purpose of heating and/or cooling the spaces. To determine which system is better from the energetic, exergetic point of view.is the most critical questions [2]. Renewable energy applications in buildings are being very common because global warming and depletion of fossil fuels. An increase in energy efficiency of construction sector would significantly reduce the greenhouse gas emissions.

Energy analysis cannot provide information about the quality of energy flows in a system, but exergy analysis is the traditional method of determining the efficient use of energy by evaluating the way energy is consumed in a system and as a result it may provide information on the quality of energy flows on a system. Besides, which components of a system are responsible for irreversibility can be determined by exergy analysis [4, 5].

About 43% of total energy consumption in France takes place in buildings. Because of this energy consumption, approximately 25% of CO2 emissions are caused by buildings [6]. As part of its national strategy for sustainable development, launched in June 2003, France agreed to reduce its energy consumption and greenhouse gas emissions by four to five times by 2050. The Climate Plan published in July 2004 is also being implemented. The annual primary energy consumption is limited to 50 kWh/m2 floor area for new buildings with the new thermal regulations of the French RT 2012 [7].

One of the successful approaches used to achieve sustainable buildings is Lowex approach, where the flow temperature of the system is very close to conditioned temperature of the space to be heated/cooled. The energy and exergy flow until building envelope from primary energy sources are examined by Lowex approach. This approach also gives information on improvement in energy and exergy amounts used at all stages of the building heating-cooling systems and HVAC-R systems [8].

Some of Lowex studies in the literature [9-13], Açıkkalp et al. 2014 has worked on building heating systems with low exergy method [9]. Yücer and Hepbaşlı evaluated the heating system in terms of exergy approach. They have reconfigured system performance for each phase, such as production, distribution, emissions, and the building envelope [10]. The performance of the heating systems of a building in Izmir in terms of exergy, energy and sustainability issues is evaluated by Hepbaşlı. They found out that the overall exergy efficiency of the heating system was around 3.3% [11]. Buyak et al. have investigated the effects of different factors such as building and human comfort parameters on indoor temperature conditions and heating requirements [12]. Sartor, K., and Dewallef, P. (2017) compared the energy and exergy consumption of different buildings and their CO2 emissions to identify the best systems in terms of energy and exergy consumption [13].

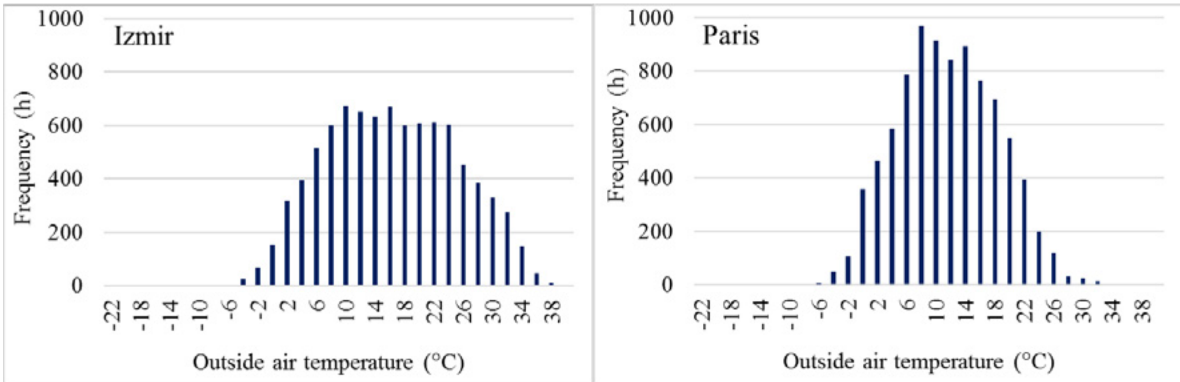


**Figure 1.** Hourly outdoor temperature frequency for the cities.

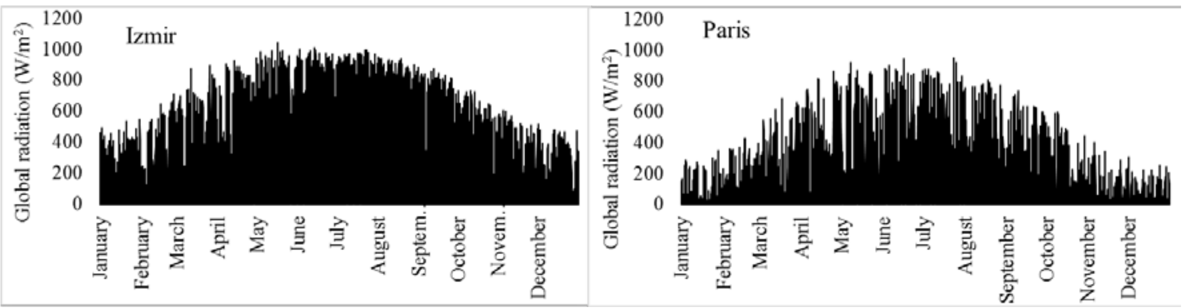


**Figure 2.** Hourly global radiation for the selected cities.

**Table 1.** The outdoor air temperature and solar radiation data of İzmir and Paris.

| | Outdoor Air Temperature (°C) | | Monthly Solar Radiation ($kWh/m^2$) | |
|---|---|---|---|---|
| | Izmir | Paris | Izmir | Paris |
| Jan. | 6.8 | 5.2 | 67.8 | 23.5 |
| Feb. | 8.0 | 6.0 | 77.7 | 39.4 |
| Mar. | 11.9 | 8.6 | 130.3 | 81.4 |
| Apr. | 15.6 | 11.8 | 167.6 | 126.1 |
| May | 21.3 | 15.6 | 211.5 | 148.4 |
| Jun. | 26.0 | 18.8 | 230.1 | 168.8 |
| Jul. | 28.5 | 20.3 | 242.3 | 166.3 |
| Aug. | 27.7 | 20.0 | 217.0 | 138.2 |
| Sep. | 22.3 | 16.6 | 168.5 | 102.1 |
| Oct. | 18.1 | 13.1 | 120.2 | 60.5 |
| Nov. | 12.4 | 8.5 | 77.6 | 28.2 |
| Dec. | 8.2 | 5.4 | 58.5 | 18.1 |
| Min. | -3.7 | -4.9 | 58.5 | 18.1 |
| Max. | 39.7 | 33.6 | 242.3 | 168.8 |
| Annual Average | 17.3 | 12.5 | 147.4 | 91.8 |

In this study, Lowex approach is applied for a building, located in İzmir and Paris, at each step of the considered energy and exergy flow from primary energy sources to environment due to reveal the inefficiency of the components and their interrelationships.

## 2. Meteorological Data

In this study, meteorological data of İzmir and Paris cities, which is crucial for all analysis, are shown in Figure 1 and Figure 2, are taken from Meteonorm software [14]. The indoor air temperature is 21 °C and winter design outside temperatures with 99.6% frequency are considered as -2.5 °C for İzmir and -3.1 °C for Paris [15]. solar radiation per square meter area is another important parameter related with outside environment to calculate the solar heat gain of the building in both cities (Figure 2 and Table 1).

## 3. System Description

Uşakizade Mansion (Figure 3) was built by Uşakizade Sadık Bey in 1860 in Göztepe, İzmir. It is a three-storey villa, including the basement. There are cellar and duty rooms in the basement of the mansion, two halls on the first floor, a dining room and a governess room. The second floor consists of 4 bedrooms and two living rooms.

Uşakizade Mansion was used as the Commander-in-Chief's Headquarters by Mustafa Kemal Atatürk during his stay in İzmir. The building became a museum in 2001.

**Table 2.** The size (area) and direction of the building components

| Building components/ Direction | Area (m²) | | | |
|---|---|---|---|---|
| | East | North | West | South |
| Exterior wall | 140.94 | 154.8 | 140.94 | 169.8 |
| Window | 31.46 | 28.6 | 31.46 | 28.6 |
| Door | | 15 | | |
| Roof | | 240 | | |
| Upper story floor | | 240 | | |
| Floors to ground | | 176 | | |

**Table 3.** U values of the construction components for the selected cities [17-19].

| City | Window | Wall | Roof / Ceiling | Floor |
|---|---|---|---|---|
| Paris | 1.3 | 0.36 | 0.20 | 0.27 |
| İzmir | 2.4 | 0.70 | 0.45 | 0.70 |

**Figure 3.** Uşakizade Mansion

The sections, elevations and plan of the building achieved by using Faro Focus Laser Scanner x330 [16]. Faro, collects the data as point clouds. After getting this point cloud data by the help of "scene" software the points are collected to have a total building 3D layout. With the help of "scene" software main building dimensions are obtained and the architectural features (area of walls/windows and direction) of the building are summarized in Table 2. The U values of the building components are taken as the values specified in the national building regulations of both cities based on the national building regulation for the selected cities are shown in Table 3.

Building primary and electricity energy flows from primary energy transformation, heat production, distribution, heating systems and from across the building envelope to the surrounding air via the indoor

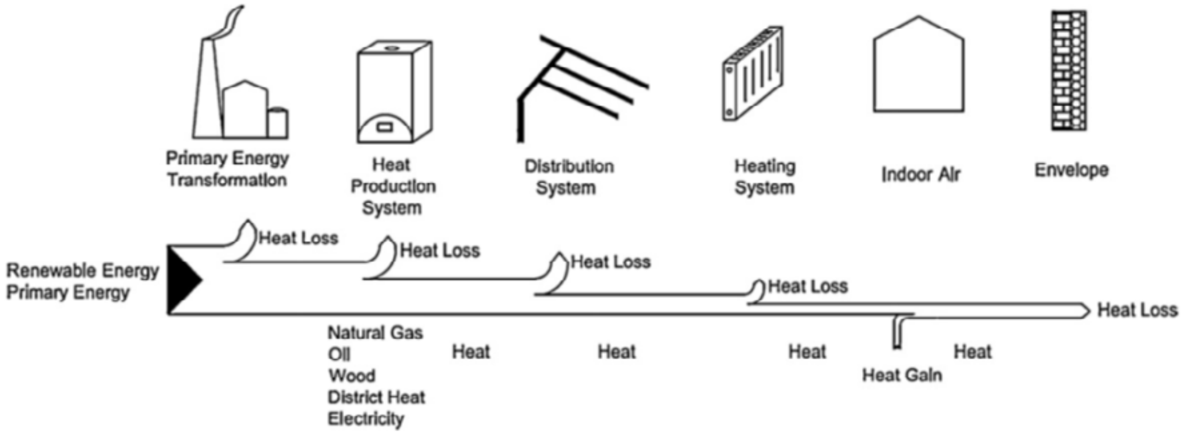


**Figure 4.** Schematic representation of the energy flow for the building [20].

**Table 4.** Main energy analysis equations

| | | |
|---|---|---|
| | **Heat Losses** | |
| **Transmission heat losses [W]** | $\dot{Q}_T = \sum\left[\left(U_i.A_i.F_{xi}\right) \cdot \left(T_i - T_o\right)\right]$ | (1) |
| **Ventilation heat losses [W]** | $\dot{Q}_V = \left[c_p.\rho.V.n_d.\left(1-\eta_V\right)\right].\left(T_i - T_o\right)$ | (2) |
| | **Heat Gains** | |
| **Solar heat gains [W]** | $\dot{Q}_S = \sum\left[I_{s,j} \cdot (1-F_f). A_{w,j} \cdot g_j \cdot F_{sh} \cdot F_{no}\right]$ | (3) |
| **Internal gains, occupants [W]** | $\dot{Q}_o = \dot{Q}''_o . no_o$ | (4) |
| **Internal gains, equipment [W]** | $\dot{Q}_e = \dot{Q}''_e . A_N$ | (5) |
| | **Other Uses** | |
| **Lighting power [W]** | $P_l = \dot{Q}_l = p_l.A_N$ | (6) |
| **Ventilation power [W]** | $P_V = p_V . V . n_d$ | (7) |
| | **Heat Demand** | |
| **Heat demand [W]** | $\dot{Q}_h = \left[\dot{Q}_T + \dot{Q}_V\right] - \left[\dot{Q}_S + \dot{Q}_o + \dot{Q}_e + \dot{Q}_l\right]$ | (8) |
| **Specific heat demand [W/m²]** | $\dot{Q}''_h = \dot{Q}_h / A_N$ | (9) |

air, are shown in Figure 4. Heat flows, both loses through the building envelope and internal gains expressed in this figure.

The same building model complying each countries building codes, TSE 825 for Turkey and Thermal Regulation RT 2012 for France are used in this study. Thus, each building model have insulation required by relevant building code. Thermal storage and energy demand for domestic hot water are not considered in this study. Six different alternatives of heating system options are studied for both cities. The considered scenarios are;

Scenario 1: Bio-Mass/Wood,

Scenario 2: A standard boiler,

Scenario 3: An electric boiler,

Scenario 4: A solar collector,

Scenario 5: An air source heat pump,

Scenario 6: A ground source heat pump (water/water).

## 4. Analysis

Calculation approach follow the Schmidt method [21] is used as a base and the related equations of the analyses are presented in Table 4 [8]. This model is used for development of an excel tool within the framework of IEA (International Energy Agency) formed within the ECBCSP (Energy Conservation in Buildings and Community Systems Programme) Annex 37 [22].

The specific energy input rate per area and per volume are:

$$\dot{E}''_{tot,pa} = \dot{E}_{tot} / A_N \quad (10)$$

$$\dot{E}''_{tot,pv} = \dot{E}_{tot} / V_N \quad (11)$$

The specific exergy input rate per area and per volume are:

$$\dot{E}x''_{tot,pa} = \dot{E}x_{tot} / A_N \quad (12)$$

**Table 5.** Constant parameters and assumptions for the analyses

| | Parameter | Unit | Symbol | Value | |
|---|---|---|---|---|---|
| Heat Losses | Air exchange rate | [ach/h] | $n_d$ | 0.4 | |
| | Heat exchanger efficiency | [-] | $\eta_V$ | 0.8 | |
| | Specific heat of indoor air | [kJ/kgK] | $C_p$ | 1.005 | |
| | Density of indoor air | [kg/m$^3$] | $\rho$ | 1.2 | |
| Heat Gains | Window frame fraction | [-] | $F_f$ | 0.3 | |
| | Total transmittance | [-] | $g_j$ | 0.58 | |
| | Solar radiation: | | | Izmir | Paris |
| | South-East to South-West, | [W/m$^2$] | $I_{s,j}$ | 85 | 53 |
| | North-West to North-East | | | 55 | 35 |
| | Other directions | | | 80 | 50 |
| | Emitted heat per occupant | [W/person] | $\dot{Q}''_o$ | 80 | |
| | Specific internal gains of equipment | [W/m$^2$] | $\dot{Q}''_e$ | 2.05 | |
| Other Uses | Specific lighting power | [W/m$^2$] | $p_l$ | 2 | |
| | Specific ventilation power | [W/m$^2$] | $p_V$ | 0.26 | |
| Distribution System | Temperature drop | [K] | | < 5 | |
| | Efficiency | [-] | $\eta_{dis}$ | 0.86 | |
| | Auxiliary energy | [W/kWheat] | $p_{aux,dis}$ | 48.89 | |
| Storage | Solar fraction | [-] | FS | 0 | |
| Heating System | Radiator inlet temperature | [°C] | $T_{in}$ | 70 | |
| | Radiator return temperature | [°C] | $T_{ret}$ | 60 | |
| | Auxiliary energy | [W/kWheat] | $p_{aux,HS}$ | 0.2 | |
| | Max. heat emission | [W/m$^2$] | $p_{heat,max}$ | 100 | |
| | Efficiency | [-] | $\eta_{HS}$ | 0.95 | |

**Table 6.** Main parameters and their values of the scenarios for heat generation.

| Parameter | Unit | Symbol | Sce. 1 | Sce. 2 | Sce. 3 | Sce. 4 | Sce. 5 | Sce. 6 |
|---|---|---|---|---|---|---|---|---|
| Efficiency | [-] | $\eta_{CB}$ | 0.65 | 0.80 | 0.98 | 0.70 | 2.5 | 1.53 |
| Primary energy factor source | [-] | $F_P$ | 0.10 | 1.30 | 3.00 | | 3 | 3.00 |
| Quality factor of source | [-] | $F_{q,S}$ | 0.95 | 0.95 | 1.00 | 0.23 | 1 | 1.00 |
| Max. supply temp. | [°C] | $T_{CB,max}$ | 70 | 90 | 100 | 80 | 80 | 35 |
| Auxiliary energy | [W/kW.heat] | $p_{aux,Gen}$ | 1.80 | 1.80 | 0.02 | 0.01 | 10 | 2 |
| Auxiliary energy constant | [W] | $P_{aux,gen,const}$ | 20 | 20 | | | | |
| Primary energy electricity factor | [-] | $F_{P,el}$ | 0.90 | | | 1.00 | 1.5 | 0.53 |

$$\dot{E}x''_{tot,pv} = \dot{E}x_{tot} / V_N \quad (13)$$

The system energy and exergy efficiencies are:

$$\eta_{sys} = \frac{\dot{E}_{building}}{\dot{E}_{tot}} \quad (14)$$

$$\psi_{sys} = \frac{\dot{E}x_{building}}{\dot{E}x_{tot}} \quad (15)$$

The system exergy destruction rate is:

$$\dot{E}x_{dest} = \left(1 - \psi_{sys}\right) \cdot \dot{E}x_{tot} \quad (16)$$

Six different generation systems are used in this study considering local fuel source availability and technical systems available in both countries. Constant parameters, relevant constants for each system and assumptions ar

**Table 7.** Results of energy flow

| Energy Flow (W) | Sce. 1 | | Sce. 2 | | Sce. 3 | | Sce. 4 | | Sce. 5 | | Sce. 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris |
| Input | 41023 | 21536 | 42895 | 22400 | 73802 | 36621 | 38468 | 20325 | 47155 | 24332 | 57551 | 29126 |
| After primary transformation | 65836 | 31235 | 29628 | 14536 | 24601 | 12207 | 64351 | 30539 | 24375 | 12103 | 24202 | 12023 |
| After generation | 22560 | 10404 | 22560 | 10404 | 22560 | 10404 | 22560 | 10404 | 22560 | 10404 | 22560 | 10404 |
| After distribution | 18710 | 8629 | 18710 | 8629 | 18710 | 8629 | 18710 | 8629 | 18710 | 8629 | 18710 | 8629 |
| After heating system | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 |
| After indoor air | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 |
| After envelope | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 | 17771 | 8196 |

**Table 8.** Results of exergy flow

| Exergy Flow | Sce. 1 | | Sce. 2 | | Sce. 3 | | Sce. 4 | | Sce. 5 | | Sce. 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (W) | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris | İzmir | Paris |
| Input | 11020 | 7769 | 41267 | 21719 | 73932 | 36751 | 7681 | 6197 | 34300 | 18473 | 50153 | 25784 |
| After primary transformation | 33272 | 16230 | 27342 | 13494 | 23726 | 11827 | 8753 | 4922 | 10299 | 5635 | 15756 | 8151 |
| After generation | 7874 | 3664 | 7874 | 3664 | 7874 | 3664 | 7874 | 3664 | 7874 | 3664 | 7874 | 3664 |
| After distribution | 6290 | 2932 | 6290 | 2932 | 6290 | 2932 | 6290 | 2932 | 6290 | 2932 | 6290 | 2932 |
| After heating system | 2553 | 1193 | 2553 | 1193 | 2553 | 1193 | 2553 | 1193 | 2553 | 1193 | 2553 | 1193 |
| After indoor air | 1420 | 671 | 1420 | 671 | 1420 | 671 | 1420 | 671 | 1420 | 671 | 1420 | 671 |
| After envelope | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

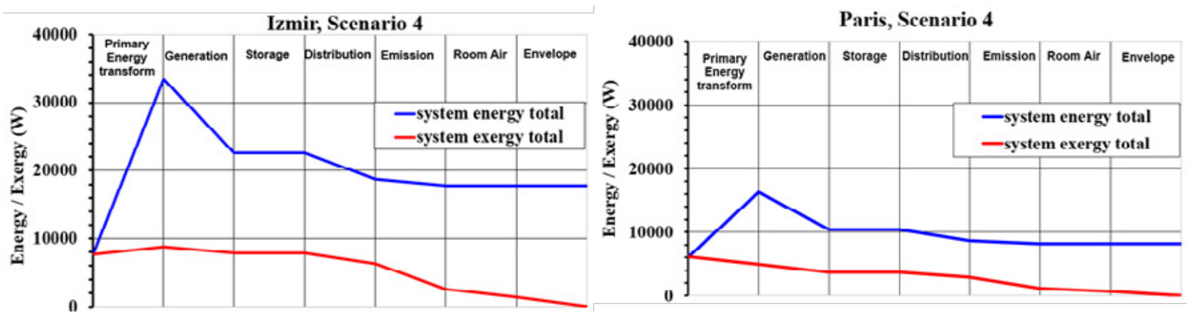


**Figure 5.** Energy and exergy flows of Scenario 4 for both cities.

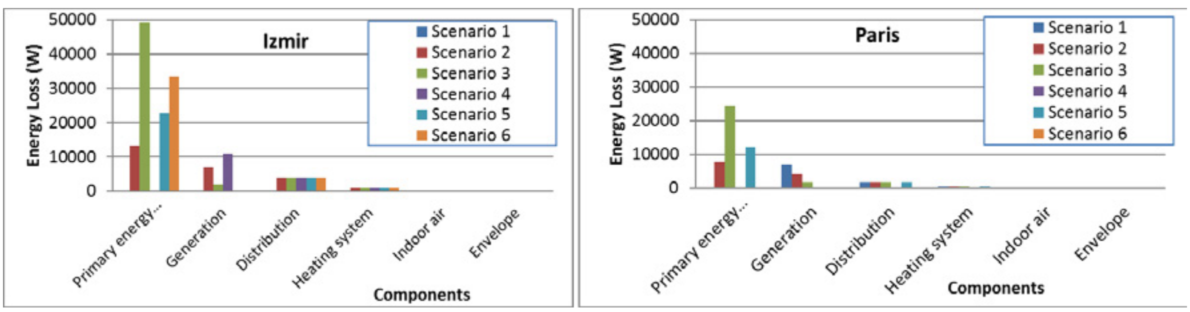


**Figure 6.** Exergy losses of the considered scenarios for both cities.

**Table 9.** Exergy losses of the considered scenarios.

| City | Components | Sce. 1 | Sce. 2 | Sce. 3 | Sce. 4 | Sce. 5 | Sce. 6 |
|---|---|---|---|---|---|---|---|
| IZMIR | Primary energy transform | -22252 | 13925 | 50207 | -1072 | 24001 | 34397 |
| | Generation | 25399 | 19468 | 15852 | 879 | 2425 | 7883 |
| | Distribution | 1584 | 1584 | 1584 | 1584 | 1584 | 1584 |
| | Heating system | 3737 | 3737 | 3737 | 3737 | 3737 | 3737 |
| | Indoor air | 1133 | 1133 | 1133 | 1133 | 1133 | 1133 |
| | Envelope | 1420 | 1420 | 1420 | 1420 | 1420 | 1420 |
| PARIS | Primary energy transform | -8460 | 8224 | 24924 | 1275 | 12839 | 17633 |
| | Generation | 12565 | 9830 | 8162 | 1257 | 1970 | 4487 |
| | Distribution | 733 | 733 | 733 | 733 | 733 | 733 |
| | Heating system | 1739 | 1739 | 1739 | 1739 | 1739 | 1739 |
| | Indoor air | 521 | 521 | 521 | 521 | 521 | 521 |
| | Envelope | 671 | 671 | 671 | 671 | 671 | 671 |

given in Table 5. Radiators with an efficiency of 0.95 are used in all heating systems. The supply/return temperatures are 70/60 °C, respectively. Main assumptions and constant parameters for each scenario for heat generation are presented in Table 6.

## 5. Results

Energetic and exergetic analysis of a three-storey building (volume of 2758.4 $m^3$ and total floor area of 656 $m^2$), located in İzmir – Turkey and Paris – France are evaluated. The design temperatures of outdoor air are considered as -2.5 °C for İzmir and -3.1 °C for Paris based on ASHRAE [15].

The specific and total heat demand rate of the building calculated as 27.09 W/m2 and 17,771 W, respectively for İzmir. Because of stricter insulation standards in force in France, the calculations show that Paris case has the specific and total heat demand rate of 12.49 W/m2 and 8,196 W, respectively.

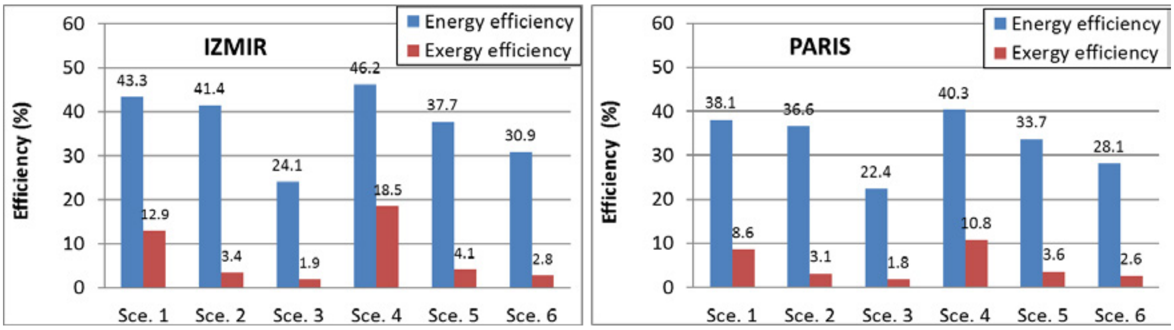


**Figure 7.** Energy and exergy efficiency values of the considered scenarios.

Subsystems and relevant energy flows calculated for each scenario are given in Table 7 and Figure 5. Energy rate range is calculated between 38,468 – 73,802 W for İzmir and 20,325 – 36,621 W for Paris, where all scenarios have the same energy demand range for indoor air, the heating and distribution system. Table 8 represents the further details of exergy analysis. Exergy rate ranges are calculated between 7,681 – 73,932 W for İzmir and 6,197 – 36,751 W for Paris. As shown in Figure 5 in each component for all scenarios exergy is consumed yet still a large amount of energy leaves through the building envelope, yet the total exergy is zero for cases for building envelope.

Figure 6 and Table 9 shows building component energy and exergy loss rates. And highest exergy loss rate is observed in primary energy transformation components in Scenario 3, electric boiler, for İzmir as 50,207 W and for Paris as 24,924 W.

Energy efficiencies are observed between %24.1 – 46.2 for İzmir and %22.4 – 40.3 for Paris as shown in Figure 7. Highest energy efficiency is observed for Scenario 4, solar collector, for both cities. In addition, lowest efficiencies of 24.1 and 22.4 for İzmir and Paris respectively are observed for Scenario 3, electric boiler. In all scenarios, Paris has better overall exergy efficiency than İzmir's because of stricter building code.

**Table 10.** Specific energy and exergy rate input per area/volume

| City | Scenarios | $\dot{E}''_{tot,pa}$ (W/m²) | $\dot{E}''_{tot,pv}$ (W/m³) | $\dot{E}x''_{tot,pa}$ (W/m²) | $\dot{E}x''_{tot,pv}$ (W/m³) |
|---|---|---|---|---|---|
| IZMIR | #1 | 62.5 | 14.9 | 16.8 | 4.0 |
| | #2 | 65.4 | 15.6 | 62.9 | 15.0 |
| | #3 | 112.5 | 26.8 | 112.7 | 26.8 |
| | #4 | 58.6 | 13.9 | 11.7 | 2.8 |
| | #5 | 71.9 | 17.1 | 52.3 | 12.4 |
| | #6 | 87.7 | 20.9 | 76.5 | 18.2 |
| PARIS | #1 | 32.8 | 7.8 | 11.8 | 2.8 |
| | #2 | 34.1 | 8.1 | 33.1 | 7.9 |
| | #3 | 55.8 | 13.3 | 56.0 | 13.3 |
| | #4 | 31.0 | 7.4 | 9.4 | 2.2 |
| | #5 | 37.1 | 8.8 | 28.2 | 6.7 |
| | #6 | 44.4 | 10.6 | 39.3 | 9.3 |

Table 10 summarizes the main results of energy and exergy analyses as specific energy and exergy rate input per area/volume. As expected, form efficiencies of individual scenario results, the minimum exergy input per area and volume are observed for Scenario 4. The minimum exergy input per area and volume for this scenario are found as 11.7 $W/m^2$ and 2.8 $W/m^3$ for İzmir and 9.4 $W/m^2$ and 2.2 $W/m^3$ for Paris respectively.

## 6. Conclusions

In this study for the cities of İzmir and Paris, six different heating system options are compared based on energy and exergy analyses for sustainable buildings. Heating system alternatives studied for a three-storey building with a total volume of 2758.4 $m^3$ and a floor area of 656 $m^2$ are biomass/wood, standard boiler, electric boiler, solar energy collector, air source heat pump, ground source heat pump (water/water). Lowex approach was applied for energy and exergy flow, and the performance of the system are determined to compare the selected scenarios for İzmir and Paris.

The main results of the study are concluded below:

- The total building energy demand rate is 17,771 W in İzmir, nearly twice of for Paris, which is 8,196 W.
- Similarly minimum and maximum primary energy rates of İzmir, 38,468 W and 73,802 W respectively are twice of Paris which are 20,325 W and 36,621 W for Paris, Electric boiler in Scenario 3 requires the highest primary energy rates.
- Among the heating systems solar collector (Scenario 4) has the lowest exergy demand rates with 7,681 W for İzmir and 6,197 W for Paris.
- For both cities, exergy loss rate occurs in primary energy transformation is highest for Scenario 2.
- Solar collector Scenario 4 has the highest overall energy efficiency of 46.2% in İzmir and 40.3% in Paris.
- Solar collector in Scenario 4 is the best option for both cities according to overall exergy efficiency.

**Nomenclature**

| | | | |
|---|---|---|---|
| A | area ($m^2$) | flex | flexibility |
| ach/h | Air changes per hour | HS | heating system |
| cp | specific heat at constant pressure (kJ/kg.K) | i | indoor, counting variable |
| $\dot{E}$ | energy rate (W) | in | input, inlet |
| $\dot{E}x$ | exergy rate (W) | ins | insulation |
| F | factor (-) | j | counting variable |
| g | total transmittance (-) | l | lighting |
| I | radiation intensity ($W/m^2$) | loss | thermal losses |
| l | length (m) | max | maximum |
| nd | air exchange rate (1/h) | N | net |
| no | number (-) | no | effect of non-orthogonal radiation |
| P | power (W) | o | outdoor, occupants |
| p | specific power, pressure ($W/m^2$, $N/m^2$) | p | primary energy |

| | | | |
|---|---|---|---|
| $\dot{Q}$ | heat transfer rate (kW) | pa | per area |
| R | pressure drop of the pipe (Pa/m) | plant | plant |
| T | temperature (K) | pv | per volume |
| U | thermal transmittance ($W/m^2K$) | q | quality |
| $\dot{v}$ | volumetric flow rate ($m^3/s$) | R | renewable energy |
| V | volume ($m^3$) | ref | reference |
| **Greek letters** | | ret | return |
| $\eta$ | energy efficiency (-) | S | solar, |
| $\psi$ | exergy efficiency (-) | s | source |
| ρ | density ($kg/m^3$) | sh | shading effects |
| Δ | difference | sys | system |
| **Subscripts** | | T | transmission |
| air | indoor air | td | temperature drop |
| aux | auxiliary energy requirement | tot | total |
| circ | circulation | usf | useful |
| dest | destruction | V | ventilation |
| dis | distribution system | w | window, water |
| dt | design temperature | x | part x |
| En | energetic | | |
| | | **Superscripts** | |
| Ex | exergetic | over dot | rate |
| e | equipment | **Abbreviations** | |
| el | electricity | COP | coefficient of performance |
| env | environment | | |
| ex | external | | |
| f | window frame, parameter | | |

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