Analysis of energy and exergy use in the Jordanian urban residential sector

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Abstract: This study presents an analysis of the energy and exergy utilisation of the Jordanian urban residential sector by considering the flows of energy and exergy through the main end uses and applications in Jordanian households. To achieve this purpose, a survey covering 200 households was conducted and energy consumption data were gathered. Exergy analysis of Jordanian urban residential sector utilisation indicates a less efficient picture than that obtained by the energy analysis. Energy and exergy efficiencies were found to be equal to 66.6% and 15.4%, respectively.

Keywords: energy; exergy; efficiency; residential; Jordan.

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1 Introduction

In this day and age, the search for optimum utilisation of energy resources is becoming increasingly important. This is due to the alarming depletion rates of high-quality energy carriers, finite natural resources, the rapid growth in population and industrialisation, and the associated increase in energy demand and consumption. Over the past few years, concern about energy consumption in Jordan has taken a new dimension. The annual fuel bill has been rapidly increasing over the past few years owing to population and economic growth combined with consecutive increases in oil prices. In 2005, Jordan's consumption of primary energy amounted to 7.028 million Ton Oil Equivalent (TOE) (Ministry of Energy and Mineral Resources, 2006). Nearly 95% of this consumption came in the form of imports of crude oil, natural gas and petroleum products. The current imports of around 100,000 barrels of crude oil per day are placing the country under extreme economic pressures.

In 2005, the residential sector represented approximately 22% of the total Jordanian energy consumption (Ministry of Energy and Mineral Resources, 2006). This sector has been affected more than any other sector by the economic and technological changes witnessed in the country. For example, in the 1960s and 1970s, kerosene was the main fuel used for cooking and water heating in urban areas in Jordan. Electricity was not widespread, and most dwellings did not have electrical appliances such as refrigerators and television sets. Gas cookers and gas heaters also were not common, particularly among low-income families (Akash and Mohsen, 1999). Currently, Liquefied Petroleum Gas (LPG) is the main fuel used for cooking and water heating. Electricity is available for almost all households, which utilise a large variety of different electrical appliances. On the other hand, most people are more conscious of energy conservation because of the relatively high energy prices and the direct economic benefits of energy savings. For example, Solar Water Heating (SWH) is common in many places since it can provide hot water for about nine months of the year. Nearly 17% of the country's dwellings use SWH systems (Department of Statistics, 2005).

The first law of thermodynamics states that the energy contained in all of the input streams to a process must be accounted for somewhere in the output streams from the same process, or accumulated within the system in which the process is occurring. This kind of analysis is used in any attempt to reduce heat loss or recover heat. However, this kind of analysis does not provide any information on the degradation of energy or quantify the usefulness of the energy content in the various streams entering or leaving the system. As an example, owing to this kind of analysis, a home electric heater could be found free of losses of any kind, but a more complete analysis would consider the losses inherent in the quality of the energy carrier.

To compare the value (quality) of the various energy carriers, it is necessary to determine the equivalents of each energy quantity at a particular grade level. This can be done with the introduction of exergy, which overcomes the limitations of the first law of thermodynamics and is based on both the first and second laws of thermodynamics (Moran, 1982; Szargut et al., 1988). An exergy analysis can identify the locations of energy degradation and rank them in terms of their significance (Moran and Shapiro, 2000). This knowledge is useful in directing the attention of process design engineers and research engineers to aspects that offer the greatest opportunities for improvement.

Recently, the concept of exergy has received great attention from scientists, researchers, and engineers (Dincer et al., 2004). The exergy concept has been used to analyse the energy utilisation of a country to gain insights into its efficiency. This approach was first used by Reistad (1975) who applied it to the US economy in 1970. Since then, it has been adopted by several researchers for other countries (Rosen, 1992; Schaeffer and Wirtshafter, 1992; Wall, 1990); a summary of different countries' exergy analyses can be found in Ertesvag (2001) and Utlu and Hepbasli (2007). The concept was also applied to different sectors for different countries (Dincer et al., 2004; Rosen, 1992; Utlu and Hepbasli, 2006; Saidur et al., 2007).

However, to the authors' knowledge, such studies have never been conducted for the main sectors in Jordan. This paper is intended to be the first step in analysing the different sectors in Jordan from an exergy point of view, starting with the urban residential sector.

2 Data sources

To determine the residential energy and exergy flows and efficiencies, the energy end use quantities of a typical Jordanian household should be known. Such detailed data and information are not available in Jordan not only for the residential sector but also for most of Jordanian sectors. Since the collection and analysis of such data on a national scale is a costly process, a survey of a representative sample of 200 households of different locations and living standard in the urban area in Jordan was conducted. This survey was aimed at collecting relevant data that are necessary to complete this study, and to gain further insights into fuel and electrical energy consumption characteristics. The survey was carried out with the assistance of mechanical and industrial engineering students at the Hashemite University. Over 250 students volunteered to complete a detailed questionnaire about the energy consumption in their households. The questionnaire covered the following aspects:

- types of space heating and the quantity used for each type
- types of water heating and the quantity used for each type
- types of cooking devices and the quantity used for each type
- types of lighting and its utilisation time and power rating
- detailed information about all common electrical appliances that can be found in a Jordanian household, including the power rating and the utilisation time.

In all questions, the level of ownership has been asked for each type of equipment and appliances. To ensure the quality of such a survey, the students were given a tutorial lecture to explain how to collect and record the required data correctly and efficiently. Only 200 correctly completed questionnaires were included in the analysis and nearly 50 were eliminated owing to incompleteness or inconsistency of the data. The survey was conducted in January 2007.

3 Methodology

The methodology adopted in this study was applied before by Dincer et al. (2004), who applied Resitad's approach (Reistad, 1975). The purpose of this section is to discuss the main quantities and mathematical relations necessary to conduct the energy and exergy analyses.

3.1 Exergy calculation

In principle, the exergy of matter can be determined by bringing it to the dead state by means of reversible processes. The basic formulas used in exergy analysis modelling are given below.

3.1.1 The exergy of fuel

The specific exergy of the fuel at environmental conditions reduces to chemical exergy, which can be written as

$$\varepsilon_{\mathrm{f}} = \gamma_{\mathrm{f}} H_{\mathrm{f}} \tag{1}$$

where ε_f is the fuel-specific exergy, γ_f the exergy grade function, and H_f the higher heating value of the fuel. Table 1 (Szargut et al., 1988; Reistad, 1975; Petchers, 2003; Utlu and Hepbasli, 2007) shows the higher heating value (H_f), the chemical exergy (ε_f), and the fuel exergy grade function (γ_f) of the most common fuel types considered in this study. As shown in this table, all the values of the exergy grade function are very close to unity. Consequently, the common practice in such cases is to assume that the exergy of the fuel is approximately equal to the higher heating value (Dincer et al., 2004; Rosen and Dincer, 1997).

Table 1 Higher heating value, chemical exergy, and exergy grade function for different fuels (at 25°C and atm)

Fuel	H_f (kJ/kg)	ε_f (kJ/kg)	γ_f (ε_f/H_f)
Kerosene	46,117	45,897	0.995
Propane	50,363	48,847	0.970
Butane	49,463	48,272	0.976
Diesel	44,800	42,265	0.943

3.1.2 The exergy of heat

The thermal exergy transfer, E^Q, associated with heat transfer Q_r across a system boundary r at constant temperature T_r is

$$E^Q = \left(1 - \frac{T_0}{T_r}\right) Q_r \tag{2}$$

where T_0 is the environmental temperature.

3.1.3 The exergy of work

From the definition of exergy, mechanical work, W, is identical to the physical work exergy, E^W

$$E^W = W. \tag{3}$$

Similarly, the energy and exergy can be considered identical for electricity.

3.2 Energy and exergy efficiencies

The energy efficiency (first law efficiency) is the ratio of the energy contained in the useful products of a process to the energy contained in all input streams, while exergy efficiency (second law efficiency) is the ratio of the exergy contained in the useful product to the exergy contained in all input streams. Energy efficiency (η) and exergy efficiency (ψ) are defined as:

$$\eta = \left(\frac{\text{energy in products}}{\text{total energy input}}\right) \times 100 \tag{4}$$

$$\psi = \left(\frac{\text{exergy in products}}{\text{total exergy input}}\right) \times 100. \tag{5}$$

Exergy efficiency can be often written as a function of the corresponding energy efficiencies by assuming the energy grade function (γ_f) to be equal to unity. This is valid for the fuels considered in this study as discussed earlier. This is explained in the following sections.

3.2.1 Process heating

For the electrical and fossil fuel heating processes, the energy and exergy efficiencies to produce heat Q_p at a constant temperature T_p, either from electrical energy W_e or a fuel mass m_f are as follows:

For electrical heating

$$\eta_{h,e} = Q_p / W_e \tag{6}$$

$$\psi_{h,e} = E^{Q_p} / E^{W_e} = (1 - T_o / T_p) Q_p / W_e = (1 - T_o / T_p) \eta_{h,e}. \tag{7}$$

For fuel heating

$$\eta_{h,f} = Q_p / (m_f H_f) \tag{8}$$

$$\psi_{h,f} = E^{Q_p} / (m_f H_f) = (1 - T_o / T_p) Q_p / (m_f \gamma_f H_f) \approx (1 - T_o / T_p) \eta_{h,f}. \tag{9}$$

Double subscripts indicate processes in which the quantity represented by the first subscript is produced by the quantity represented by the second, e.g., the subscripts h, e mean heating with electricity.

Equations (7) and (9) show that a value for η close to unity is important for proper utilisation of the exergy transferred from the energy source to the system. However, this alone would not ensure effective utilisation. The system temperature is also important; with exergy utilisation improving with increasing system heating temperature. Therefore, for the proper utilisation of exergy, it is desirable to have a value for η as close to unity as practical and also a good match between the sources and use temperatures (Moran and Shapiro, 2000).

3.2.2 Work and electrical production

For processes in which the output energy is either mechanical or electrical, the energy and exergy efficiencies can be considered the same.

3.3 Reference environment

To calculate exergy, the environment must be specified. The environment performs the functions of reservoirs of thermal, mechanical and chemical energy. Its intensive properties (temperature, pressure, and chemical potential) do not change significantly as a result of any of the processes under consideration, and experiences only internally reversible processes (Moran and Shapiro, 2000). Based on weather and climate condition of Jordan, this study takes the environmental conditions as 1 atm and 25°C with some exceptions as will be shown later in the analysis. The chemical composition, as adopted by Gaggioli and Petit (1977), which is recommended by Dincer et al. (2004), is taken to be air saturated with water vapour, and following condensed phases are used at 25°C and 1 atm: water (H_2O), gypsum ($CaSO_4 \times 2H_2O$) and limestone ($CaCO_3$).

4 Results and analysis

4.1 Energy consumption

4.1.1 Electrical energy used by appliances

The electrical energy used by each appliance is a function of the appliance power rating, total utilisation hours, and ownership level. These parameters have been estimated from the survey questionnaire. Table 2 shows these parameters for the most common appliances that can be found in Jordanian households. The ownership level results obtained from this survey are very close to those obtained from a general population and houses survey carried out by the Jordanian Department of Statistics (DOS) in 2004 (Department of Statistics, 2005). For example, the ownership levels of washing machines, refrigerators and TVs were found to be equal to 0.97, 0.90 and 1.06, respectively. This agrees well with the results of the DOS survey, which indicate ownership levels of 0.93, 0.94 and 1.01, respectively, for the same appliances mentioned above. This consistency increases the confidence in the results of the conducted survey, which were more detailed, and comprehensive than those obtained by the DOS survey.

Table 2 Average power rating, ownership level, annual utilisation time and energy use of different appliances

Appliance	*Power rating* (W)	*Ownership level* (*appliance/house*)	*Utilisation time* (*hour*)	*Total energy* (*MJ/house*)
AC	1,432	0.11	1,533	831
Fan	60	1.58	1,911	652
Washing machine	877	0.97	416	1,221
Vacuum cleaner	1,466	0.52	153	420
Iron	1,381	0.97	226	1,090
Microwave	1,236	0.20	99	40
Refrigerator-Freezer	164	0.90	3,008	1,669
PC	100	1.05	2,281	205
Satellite Receiver	30	0.61	4,343	263
TV	95	1.06	4,365	1,508
Hi Fi	25	0.70	1,018	70
Mobile Phone charger	17	1.84	872	37
Water cooler	102	0.38	493	69
Hair dryer	1,400	0.67	80	270
Blender mixer	375	0.79	110	117
Total				*8,462*

The electrical energy used by appliance *i* (E_i) can be determined using the following formula:

$$E_i = OL_a \times P_a \times U_a \times C_1 / C_2. \quad (10)$$

where OL_a is the ownership level (appliance/household), P_a the power rating of appliance (W), U_a the utilisation time of appliance (h/yr), C_1 the conversion factor from kWh to MJ (3.6) and C_2 the conversion factor from Wh to kWh (1000). As an example, the annual electrical energy used by a television set ($E_{T.V.}$) can be determined as follows:

$$E_{T.V.} = 1.01 \times 95 \times 4365 \times 3.6 / 1000 = 1508 \text{ MJ/yr.}$$

The sum of annual electrical energy (E_a) used by all appliances can be calculated using the following equation:

$$E_a = \sum_i E_i. \tag{11}$$

4.1.2 Energy used by space heating, water heating and cooking

The average consumption of fuel for space heating, water heating, and cooking were estimated directly from the survey results as the questionnaire contained questions about the quantity of purchased energy for each of these end uses. The electricity consumed by electrical heaters used for space heating was estimated using equation (10). However, it is difficult to estimate the electricity consumption for water heating using this equation since the usual behaviour is to keep the heater on to run automatically whenever the water temperature falls below a pre-set value. Therefore, the following equation is used to estimate the electricity used, E_{WH}, for water heating

$$E_{WH} = \frac{Q_S \times C_p \times \Delta T_S}{\eta_{WH}} \times SD + \frac{Q_W \times C_p \times \Delta T_W}{\eta_{WH}} \times WD \tag{12}$$

where Q_S and Q_W represent the daily consumption of hot water during summer and winter, respectively (kg/day), C_p the specific heat of water (kJ/kg.^{o}C), ΔT_S and ΔT_W are the temperature rise of water for summer and winter, respectively, SD and WD the number of summer and winter days, respectively, and η_{WH} the energy efficiency of electrical water heater. The solar energy can also be estimated using equation (12) by eliminating the second term and taking the solar water heater efficiency as 30%.

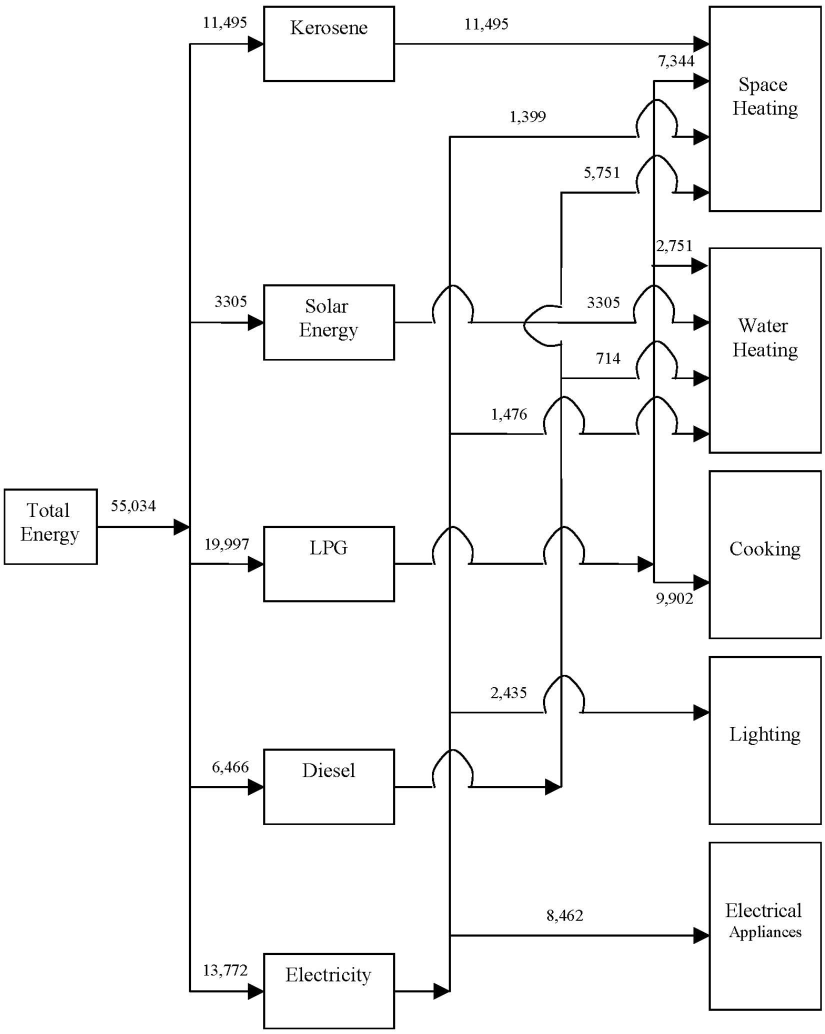
4.1.3 Electrical energy used by lighting

The types of lighting and its utilisation time and power rating have been found from the survey. The electricity consumed by lighting can then be estimated using equation (10).

4.2 End use model of the Jordanian residential sector

To determine the overall energy and exergy efficiencies for the residential sector, the consumption of total electrical and fossil fuel energy within the sector must be known as well as the proportion of energy consumed for each end use process within the sector. Fortunately, there are primary end uses of energy for the residential sector. These end uses are: space heating, water heating, cooking, lighting, and electrical appliances. Based on the calculations of the previous sections, a model in the form of an energy flow diagram that explains how total energy input is distributed and routed to different categories of end uses has been developed. This model is shown in Figure 1.

Figure 1 Typical annual energy flow of a Jordanian household (MJ)



4.3 *Energy and exergy efficiencies*

4.3.1 *Energy and exergy efficiencies of electrical appliances*

As stated before, the exergy efficiency is dependent on energy efficiency, the environment temperature and the product temperature. The average operating energy efficiency in addition to the environment and product temperatures for the appliances considered in this work are given in Table 3 (Rosen and Dincer, 1997; Reistad, 1975). These values were used to calculate the exergy efficiency indicated in the same table. For example, the exergy efficiency, ψ_e, for the iron appliance is calculated using equation (7) as follows:

$$\psi_e = \left(1 - \frac{298}{432}\right) \times 98 = 30.40\%.$$

Note that for the appliances of electrical and mechanical energy output, the energy and exergy efficiencies are identical.

Table 3 Energy efficiency, product and environment temperatures, exergy efficiency and share of used energy for different types of appliances

Appliance	η_e (%)	T_p (K)	T_o (K)	ψ_e (%)	*Share of used energy* (%)
AC	90	293	303	3.07	9.82
Fan	80	–	–	80	7.71
Washing machine	80	–	–	80	14.43
Vacuum cleaner	70	–	–	70	4.96
Iron	98	432	298	30.40	12.88
Microwave	70	–	–	70	0.47
Refrigerator-Freezer	60	265	298	7.47	19.72
PC	70	–	–	70	2.42
Satellite Receiver	70	–	–	70	3.11
TV	80	–	–	80	17.82
Hi Fi	70	–	–	70	0.83
Mobile phone charger	70	–	–	70	0.44
Water cooler	70	283	303	4.95	0.82
Hair dryer	70	313	298	3.35	3.19
Blender mixer	80	–	–	80	1.38
Total	*77.7*			*47.5*	*100.00*

Calculation of overall energy and exergy efficiencies, η_a and ψ_a, respectively, of all appliances can be carried out using the share of each appliance in the total used energy as a weighting factor

$$\eta_a = \sum_i \eta_{ei} \times F_{ei} / 100 \tag{13}$$

$$\psi_a = \sum_i \psi_{ei} \times F_{ei} / 100 \tag{14}$$

where η_{ei} and ψ_{ei} are the energy and exergy efficiencies of appliance i (%), F_{ei} the fractional energy usage for appliance i(%). Applying these equations, the overall weighted energy and exergy efficiencies for all appliances are 77.7% and 47.5%, respectively.

4.3.2 Energy and exergy efficiencies of lighting

From the survey, lighting electrical consumption is found to be approximately equally divided between fluorescent and bulb types with energy and exergy efficiencies of about 20% and 18.5%, and 5% and 4.5%, respectively (Rosen and Dincer, 1997; Ileri and Gurer, 1998). Combining the relevant energy and exergy efficiencies for lighting, the calculated energy and exergy efficiencies are 12.5% and 11.5%, respectively.

4.3.3 Energy and exergy efficiencies of cooking

Liquefied Petroleum Gas (LPG) is the main fuel used for cooking while electrical energy is rarely utilised. Therefore, the contribution of electrical energy in cooking is not included in this study. The average energy efficiency and product temperature are assumed to be 65% and 374 K, respectively (Dincer et al., 2004). The exergy efficiency, ψ_c, can then be calculated as

$$\psi_c = \left(1 - \frac{298}{374}\right) \times 65 = 13.21\%.$$

4.3.4 Energy and exergy efficiencies of water heating

Electricity, diesel, LPG, and solar energy are the main sources used for water heating in Jordan with shares of 17.9, 8.7, 33.4 and 40.0%, respectively. The energy efficiencies are assumed to be 90, 80, 80 and 30% for electricity, diesel, LPG, and SWH appliances, respectively (Utlu and Hepbasli, 2003). Taking the product and ambient temperatures as 348 K and 298 K, respectively, the exergy efficiencies for electrical, diesel, LPG, and SWH appliances are 12.9, 11.5, 11.5 and 4.3%, respectively. The overall weighted energy and exergy efficiencies are then found to be equal to 61.8% and 7.2%, respectively.

4.3.5 Energy and exergy efficiencies of space heating

Electricity, diesel, LPG, and kerosene energy are the main sources used for space heating with shares of 5.4, 22.1, 28.3 and 44.2%, respectively. The energy efficiencies are assumed to be 98, 80, 65 and 65% for electricity, diesel, LPG, and kerosene space heating appliances, respectively (Utlu and Hepbasli, 2003). Taking the product and ambient temperatures as 323 K and 283 K, respectively, the exergy efficiencies for electrical, diesel, LPG, and kerosene space heating appliances are 12.1, 9.9, 8.1 and 8.1%, respectively. The overall weighted energy and exergy efficiencies are then found to be equal to 70.1% and 8.7%, respectively.

4.3.6 Overall energy and exergy efficiencies of the residential sector

Finally, the overall weighted energy and exergy efficiencies for the Jordanian residential sector are calculated from the energy and exergy efficiencies of the end uses estimated earlier. The weighting factor of each end use is the ratio of the total energy used by that end use to the total energy used by all end uses. Results are summarised in Table 4. It can be seen that the exergy efficiency is much lower than its corresponding energy efficiency for all end uses. The overall weighted energy and exergy efficiencies are 66.6% and 15.4%, respectively. The most significant differences between energy and exergy efficiencies are attributed to heating processes. Among the different end uses, electrical appliances are the most efficient end uses for energy and exergy utilisation. Furthermore, most electrical appliances have identical energy and exergy efficiency values since their output is either electrical or mechanical energy.

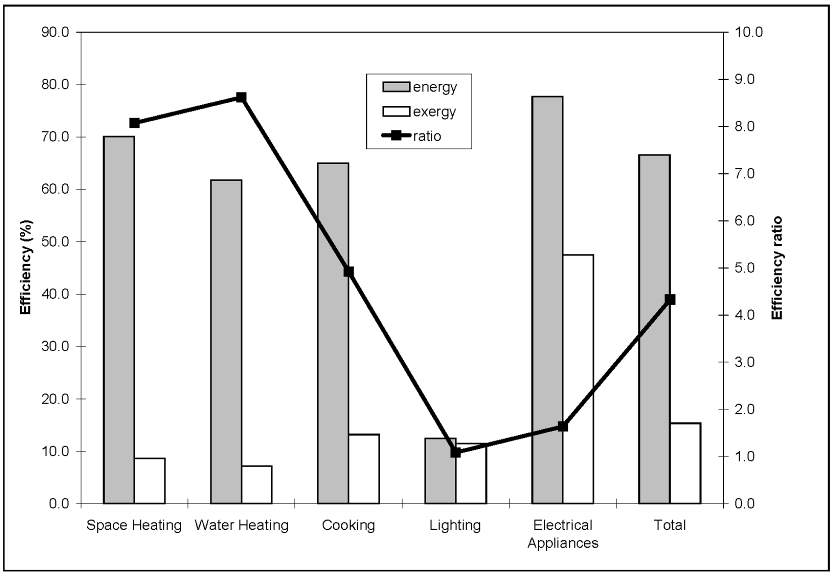
This study indicated that exergy utilisation is worse than energy utilisation in the Jordanian urban residential sector. However, this is the case for most studies found in the literature. By comparison, exergy efficiencies for the residential–commercial sector are reported to be about 30% for Malaysia in 1997–2004 (Saidur et al., 2007), 9% for Saudi Arabia in 1990–2001 (Dincer et al., 2004), 12, 13 and 2% for Brazil in 1987, Sweden in 1994, and Italy in 1990, respectively (Ertesvag, 2001), 9.33% for Turkey in 2002 (Utlu and Hepbasli, 2006), and 14% for Canada in 1986 (Rosen, 1992). The exergy efficiency variation from country to country can be attributed to different assumptions adopted by the investigators as well as the differences in the residential sector structure. However, most of the countries, including Jordan, represent a big potential for increasing the exergy efficiency.

Table 4 Calculated average energy efficiency, exergy efficiency, and annual energy consumption of Jordan's residential sector

End use	η (%)	ψ (%)	*Energy consumption* (MJ/house)	*Share* (%)
Space heating	70.1	8.7	25,989	47.22
Water heating	61.8	7.2	8,246	14.98
Cooking	65	13.2	9,902	17.99
Lighting	12.5	11.5	2,435	4.42
Electrical appliances	77.7	47.5	8,462	15.38
Total	*66.6*	*15.4*	*55,034*	*100.00*

As discussed before, for the proper utilisation of exergy, it is desirable to have a value for η as close to unity as practical and also a good match between the supply energy quality and the end use process. The latter can be recognised by estimating the ratio of energy to exergy efficiencies for each end use. Figure 2 shows the energy efficiency, exergy efficiency as well as the ratio between them for different end uses of the residential sector in Jordan. A proper match is made whenever the value of the energy efficiency/exergy efficiency ratio approaches unity. Higher values indicate inefficient utilisation of energy resources. Again, space and water heating stand out as the most inefficient end uses in the Jordanian urban residential sector. Owing to their high share in the total energy used in this sector, they are responsible for the relatively high value of the sector's overall ratio.

Figure 2 Energy efficiency, exergy efficiency and the ratio between energy and exergy efficiencies for different end uses of the urban residential sector in Jordan



4.4 Energy and exergy products and losses

Energy and exergy flow diagrams are very helpful in identifying the energy and exergy products and losses in order to distinguish between high and low efficiency end uses. The results of the analysis presented earlier were used to establish the energy and exergy flow diagrams of the Jordanian urban residential sector. These diagrams are presented in Figures 3 and 4, which show energy and exergy inputs, products and losses for each end use of the sector.

Figure 3 Energy flow diagram of the urban residential sector in Jordan (MJ/yr household)

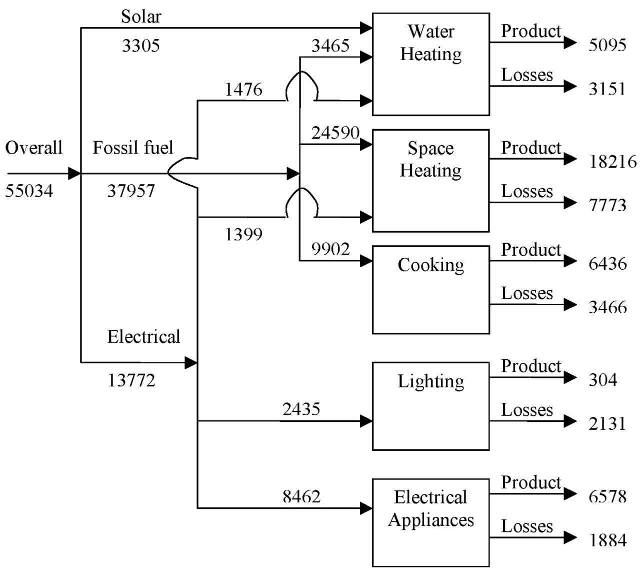
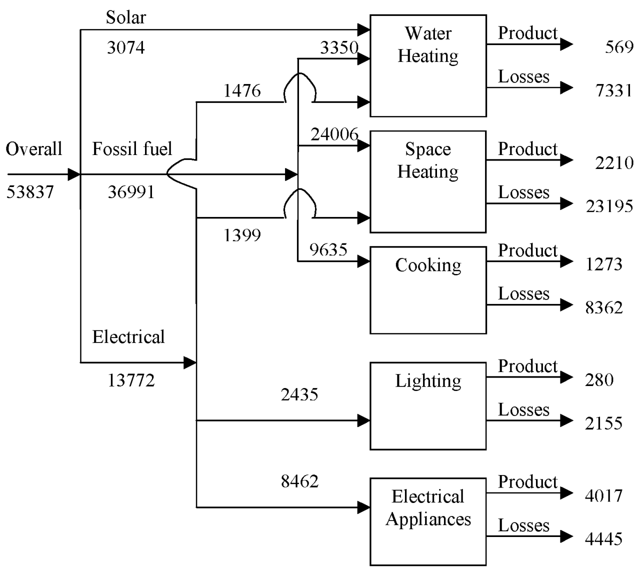


Figure 4 Exergy flow diagram of the urban residential sector in Jordan (MJ/yr household)



5 Conclusions

In this paper, energy and exergy utilisation in the Jordanian urban residential sector has been analysed by considering the energy and exergy flows for the year 2006. The analysis is done based on a survey conducted for 200 households. The estimation methods and assumptions are clearly described in this paper, so the methods can be readily modified for different data and assumptions. The variations of energy and exergy efficiencies have been studied and analysed for the most common devices that can be found in a typical Jordanian urban household.

The average overall energy and exergy efficiencies for the Jordanian urban residential sector are found to be 66.6% and 15.4%, respectively. The exergy efficiency appears to be much lower than its corresponding energy efficiency due to the large amount of losses taking place in space and water heating and cooking end uses. The most energy- and exergy-efficient end use is the electrical appliances while lighting and space heating end uses are the least energy and exergy-efficient end uses, respectively.

This study shows that there is significant potential for increasing the exergy efficiency of the urban residential sector in Jordan. This, however, cannot be achieved without a planned effort on the policymaking level through incentives scheme combined with programs for raising the awareness of the importance and benefits of energy-efficient technologies. Also, this study emphasises, as has been concluded before for different countries, that the present technique in analysis is beneficial for analysing sectoral energy and exergy utilisation. This paper is intended to be the first step in analysing the different energy-consuming sectors in Jordan from an exergy point of view.

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Nomenclature

C_1	Conversion factor from kWh to MJ
C_2	Conversion factor from W to kWh
C_p	Specific heat of water (kJ/(kg°C))
E	Exergy (kJ)
E_a	Electrical energy by all appliances (MJ/yr)
E_i	Electrical energy used by appliance *i* (MJ/yr household)
E_{WH}	Electricity used for water heating (MJ)
F_{ei}	Fractional energy usage for appliance i (%)
H_f	Higher heating value (kJ/kg)
m_f	Fuel mass (kg)
OL_a	Ownership level (appliance/household)
P_a	Power rating of appliance (W)
Q	Heat transfer (kJ)
Q_S	Daily consumption of hot water during summer (kg)
Q_W	Daily consumption of hot water during winter (kg)
SD	Number of summer days
T	Temperature (K)
U_a	Utilisation time of appliance (h/yr)
W	Mechanical work (kJ)
WD	Number of winter days
W_e	Electrical energy (kJ)
ε_f	Fuel-specific exergy (kJ/kg)
γ_f	Exergy grade function
η	Energy efficiency (%)

ψ	Exergy efficiency (%)
ΔT	Temperature rise (°C)
η_a	Overall energy efficiency of all appliances (%)
ψ_a	Overall exergy efficiency of all appliances (%)
ψ_c	Exergy efficiency for cooking (%)
η_{ei}	Energy efficiency of appliance *i* (%)
ψ_{ei}	Exergy efficiency of appliance *i* (%)
Subscripts	
h,e	Heating by electricity
h,f	Heating by fuel
o	Environment
p	Product heat
r	System boundary
S	Summer
W	Winter
WH	Water heating
Superscripts	
Q	Heat transfer
Q_p	Product heat
W	Mechanical work
W_e	Electrical energy