Applied Energy 88 (2011) 4411–4423

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A comparative investigation of various greenhouse heating options using exergy analysis method

Arif Hepbasli *

Department of Mechanical Engineering, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

ARTICLE INFO

Article history:
Received 13 March 2011
Received in revised form 4 May 2011
Accepted 15 May 2011
Available online 12 June 2011

Keywords:
Energy
Exergy
Greenhouses
LowEx
Renewable energy
Sustainability

ABSTRACT

This study deals with modeling and analyzing the performance of greenhouses from the power plant through the heating system to the greenhouse envelope using exergy analysis method, the so-called low exergy or LowEx approach, which has been and still being successfully used in sustainable buildings design, for the first time to the best of the author's knowledge. For the heating applications, three options are studied with (i) a solar assisted vertical ground-source heat pump greenhouse heating system, (ii) a wood biomass boiler, and (iii) a natural gas boiler, which are driven by renewable and non-renewable energy sources. In this regard, two various greenhouses, the so-called small greenhouse and large greenhouse, considered have heat load rates of 4.15 kW and 7.5 MW with net floor areas of 11.5 m^2 and 7.5 ha, respectively. The overall exergy efficiency values for Cases 1–3 (solar assisted vertical ground-source heat pump, natural gas boiler and wood biomass boiler) of the small greenhouse system decrease from 3.33% to 0.83%, 11.5% to 2.90% and 3.15% to 0.79% at varying reference state temperatures of 0 to 15 °C while those for Cases 1 and 2 (wood biomass and natural gas boilers) of the large greenhouse system decrease from 2.74% to 0.11% and 4.75% to 0.18% at varying reference state temperatures of −10% to 15 °C. The energetic renewability ratio values for Cases 1 and 3 of the small greenhouse as well as Case 1 of the large greenhouse are obtained to be 0.28, 0.69 and 0.39, while the corresponding exergetic renewability ratio values are found to be 0.02, 0.64 and 0.29, respectively.

1. Introduction

Various policies have been formulated in many countries around the world to aim at decreasing carbon dioxide emissions, while many countries have also established policies towards increasing the share in renewable energy utilization. Both are parts of a global response to the climate change [1]. Especially in analyzing 100% renewable energy systems, which will be technically possible in the future, and may even be economically beneficial compared to the business-as-usual energy system, energy savings, efficient conversion technologies and the replacement of fossil fuels with renewable energy are essential elements to consider [2].

As a consequence of the latest reports on climate change and the need for a reduction in CO_2 emissions, huge efforts must be made in the future to conserve high quality, or primary energy, resources [3,4]. A new dimension will be added to this problem if countries with fast growing economies continue to increase their consumption of fossil energy sources in the same manner as they do now. Even though there is still considerable energy saving potential in building stock, the results of the finished IEA ECBCS Annex 37, Low Exergy Systems for Heating and Cooling of Buildings, show that there is an equal or greater potential in exergy management [4,5].

The amount of energy used in agricultural production, processing and distribution is significantly high. Sufficient supply of the right amount of energy along with its effective and efficient utilization is necessary for an improved agricultural production. It has also been reported that crop yields and food supplies are directly linked to energy [6].

Various types of heating systems have been used in greenhouses for meeting the heating and cooling requirements. Steam or hot water radiation systems, which utilize steam or hot water supplied through pipe networks running through the greenhouse, and hot air unit heaters, are among some applications. The heating requirements of the greenhouse may be generally met by these systems, but the temperature distribution patterns within the greenhouse associated with such systems are readily influenced by the outdoor weather conditions. In addition, such systems are usually not able to control and maintain the required humidity levels within the greenhouse, which also affect the growth of crops. Thus, there is a great potential in employing a heat-pump system for greenhouse air-conditioning based on its ability to perform the multi-function of heating, cooling and dehumidification [7].

* Tel.: +966 14676677; fax: +966 14672636.
E-mail addresses: ahepbasli.c@ksu.edu.sa, arifhepbasli@gmail.com

0306-2619/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2011.05.022

Nomenclature

A	area (m^2)
c	specific heat (kJ/kgK)
COP	coefficient of performance (–)
$\dot{E}$	energy rate (W)
$\dot{E}x$	exergy rate (W)
f	approximation factor (–), factor (–)
F	factor (–)
l	length (m)
N	percentage of equipment resistance
P	power (W)
p	specific power, pressure (W/m^2, N/m^2)
$\dot{Q}$	heat transfer rate (kW)
R	pressure drop of the pipe (Pa/m), thermal resistance (m^2 K/W), ratio (–)
SI	sustainability index (–)
T	temperature (K)
$\dot{v}$	volumetric flow rate (m^3/s)
V	volume (m^3)

Greek letters

η	energy efficiency (–)
ψ	exergy efficiency (–)
Δ	difference

Subscripts

air	indoor air
aux	auxiliary energy requirement
c	construction type
circ	circulation
dis	distribution system
En	energetic
Ex	exergetic
el	electricity
env	environment
Ge	generation
gp	generator position
gh	greenhouse
HS	heating system
h	heat
heat	heater
i	indoor, counting variable
in	input, inlet
ins	insulation
l	lighting
max	maximum
N	net
o	outdoor, occupants
p	primary energy, constant pressure
q	quality
R	renewable energy
r	renewability
ref	reference
ret	return
S	solar
s	source
td	temperature drop
tot	total
usf	useful
V	ventilation
w	wind
0	reference (dead) state

Superscripts

over dot	rate

Abbreviations

COP	coefficient of performance
ECBCS	energy conservation in buildings and community systems programme
IEA	international energy agency
LGH	large greenhouse
LowEx	low exergy
SAVHP	solar assisted vertical ground-source heat pump
SGH	small greenhouse

A geothermal heat pump or ground-source heat pump (GSHP) is a central heating and/or cooling system that pumps heat to or from the ground to provide heating, air conditioning and, in most cases, hot water. Studies have shown that approximately 70% of the energy used in a GSHP system is renewable energy from the ground [8]. In this regard, GSHP systems have become increasingly popular for both residential and commercial heating and cooling applications. These systems have been recognized to provide viable, environmentally friendly alternatives to conventional unitary systems. They can make significant contributions to reductions in electrical energy utilization, and offer more effective demand-side management [9].

There are basically six different ground-source heating systems, which are applied to greenhouses: (a) finned pipe, (b) standard unit heaters, (c) low-temperature unit heaters, (d) fan-coil units, (e) soil heating, and (f) bare tube [10]. The performance of the low temperature unit heaters falls between that of standard unit heaters and fan-coil units. Among the above-mentioned heating systems, the soil heating (ground heating by coils embedded to the ground), which involves using the floor of the greenhouse as a large radiator, requires lower heating fluid temperatures, and especially helpful to protect the plant root zone temperature, rather than simply heating the air. In addition, because the air is not needed to heat too much, energy is saved, and lower heating fluid temperature increases the COP values [10,11].

Exergy may be defined in various ways as follows [12,13]: (i) The quality of energy , (ii) The capacity of energy to cause change, (iii) The maximum work that can be obtained from a given form of energy using the environmental parameters as the reference state, and (iv) A measure of the departure of the state of the system from the state of the environment. In this regard, it should be noticed that exergy is always evaluated with respect to a reference environment (i.e., dead state), while the selection of dead state conditions is arbitrary, but depends on some criteria. Exergy analysis has been viewed as a very useful tool, which can be successfully utilized in the design, simulation and performance assessment of energy related systems. Exergy analysis is relevant in identifying and quantifying both the consumption of useful energy (exergy) used to drive a process as well as the irreversibilities (exergy destructions) and the losses of exergy. The latter are the true inefficiencies and, therefore, an exergy analysis can highlight the areas of improvement of a system. Exergy measures the material's true potential to cause a change [13].

Trends in energy demand for heating and cooling could be very important for the development of the energy system. Of course, the key issue is how to make buildings energetically sustainable?

Exergy as a thermodynamic analysis tool can help achieve this objective. The LowEx approach is one of these approaches, which may be used in sustainable buildings design [14]. The main objective of this approach is to constitute a sustainable built environment, while future buildings should be planned to use sustainable energy sources for HVAC applications [15].

In the last few years, also due to the increasing interest in low temperature heating and high temperature cooling systems, a research co-operation in a working group of the International Energy Agency (IEA) has been formed within the Energy Conservation in Buildings and Community Systems Programme (ECBCSP): "Low Exergy Systems for Heating and Cooling of Buildings" [16]. The number of studies on exergetic analysis of LowEx heating and cooling systems in buildings is relatively low [4,17–24], while there are not any studies on evaluating the performance of greenhouses from the power plant through the heater to the greenhouse envelope using LowEx approach in the open literature to the best of the author's knowledge. This was the prima motivation in doing the present contribution. In this regard, the LowEx approach is applied to a small greenhouse explained in the author's common studies [11,25,26] based on the experimental values and a large greenhouse [27] with net floor areas of 11.5 m^2 and 7.5 ha, respectively. Three heating options, namely (i) a vertical ground-source heat pump system [26], (ii) a wood biomass boiler [27,28], and (iii) a natural gas boiler, are considered for performance analysis and assessment purposes through energy and exergy efficiencies. The energetic and exergetic renewability ratios are also utilized here along with sustainability index.

2. System descriptions

In this study, two various greenhouses are mainly considered as case studies. The first one (the so-called small greenhouse: SGH) has three heating options with a heat load of 4.15 kW for a greenhouse of 11.5 m^2 [11,25,26], namely (i) a solar assisted vertical ground-source heat pump (SAVHP) greenhouse heating system, (ii) a wood biomass boiler, and (iii) a natural gas boiler. The second one (the so-called large greenhouse: LGH) has an actual heat power of 7.5 MW specified for a 7.5-ha greenhouse [27], which has two types of heating options with wood biomass and natural gas boilers. Table 1 lists some technical specifications of the systems studied [26–28], while Fig. 1 illustrates a schematic of the SAVHP greenhouse heating system [11], which is an air/refrigerant vapor compression solar assisted heat pump composed mainly of a rated power of electric motor driving 1.4 kW compressor, 6.66 kW condenser, 8.2 kW evaporator, expansion device equipped with a series of capillary tubes with 1.5 m long and inside diameter is 1.5 mm. Beside this, the system mainly consists of three separate circuits: (i) the ground coupling circuit with solar collector (brine circuit or water–antifreeze solution circuit), (ii) the refrigerant circuit (or a reversible vapor compression cycle) and (iii) the fan coil circuit for greenhouse heating (water circuit).

Greenhouses use water-tube boilers (natural gas-fired or biomass-fired), which are connected to a close-loop water system for providing heat in the greenhouses. Hot water is circulated for heating purposes and returned to the boiler as cold or low-temperature water. Natural gas boilers are more commonly used in the greenhouse industry due to the relatively low capital cost and their relatively small physical size. Moreover, burning natural gas can generate CO_2 for injection into a greenhouse. In contrast, biomass boilers are larger in size and have high capital costs [27].

Fig. 2 shows the energy flows in forms of primary and electricity for a greenhouse from primary energy transformation through the heat production system and a distribution system to a heating system, and from there, via the indoor air, across the greenhouse envelope to the surrounding air [16,29].

For the heating applications, three options are studied with (i) a SAVHP, (ii) a wood biomass boiler (iii) a natural gas boiler. In Case 1, a SAVHP is used for heat production. Its COP is 3.1 with a maximum supply temperature of 56 °C based on the experimental values [26] although in today's technology higher COP values may be obtained. For Case 2, a wood biomass boiler utilizing wood pellets is used for heat production. Its efficiency is assumed to be 0.88 with a maximum supply temperature of 70 °C. In Case 3, a natural gas boiler is used for heat production with an efficiency of 0.925. Additionally, for all cases of heating systems, the fan-coils (or radiators) have the flow and return temperatures specified as 56 °C and 46 °C with a heat loss/efficiency of 0.95, respectively. The distribution systems of all cases are considered to have a good insulation with a heat loss of about 9% and a temperature drop of 5 °C. The domestic heat water energy demand is not considered in this study.

3. Analysis

In this study, the methodology and relations used are based on a pre-design analysis tool, which has been produced during the ongoing work for the IEA-ECBCS Annex 37 to increase the understanding of exergy flows in buildings and to be able to find possibilities for further improvements in energy utilization in buildings [16,30,31]. The methodology has been developed for buildings, while the LowEx network [31], in which the author is a member, has conducted various studies towards applying this methodology to different low exergy heating and cooling systems. In this regard, the present study utilizes this methodology for two various greenhouses.

In the first section, the general project data and boundary conditions are checked out. V and A_N are the internal volume of the greenhouse and the net floor area, respectively. T_o is the outdoor temperature and T_i is the indoor temperature in the design conditions. The outdoor temperature is taken as the reference temperature T_{ref} for analysis purposes.

The heat demand rates of the greenhouse envelope ($\dot{Q}_h$) include all heat flows, heat losses via the envelope, and internal gains occurring inside the greenhouse and have to be summed up to create the following energy balance, which refers to the first law of thermodynamics:

$$\dot{Q}_h = \text{Sum of heat losses rate} - \text{Sum of heat gains rate} \tag{1}$$

A heat loss calculation is the first step in determining heating system capacity before selecting the system and its various components. The heating system should be properly sized to needs of greenhouse under extreme weather conditions. The rate of heat loss from the greenhouse may be shortly calculated using the following equation [26,32] or other approaches proposed in the literature.

$$\dot{Q}_{gh} = [(A_1/R_1) + (A_2/R_2) + \cdots](T_i - T_o) f_w f_c f_s \tag{2}$$

where f_c is the construction type factor, f_s is the system factor and f_w is the wind factor, respectively, while $(T_i - T_o)$ is the temperature difference between greenhouse inside and outdoor temperatures. For the SAVHP greenhouse heating system with a total glass reinforced plastic (GRP) surface area of 48.51 m^2, the thermal resistance (R) of GRPs is 0.16 m^2K/W, while the factors of f_c , f_s and f_w are 1.08, 1.00 and 1.13, respectively [26].

The heat demand rate is usually expressed in a specific number in order to be able to compare different greenhouses with each other:

Table 1
Some technical specifications of various greenhouse heating systems studied [11,27,28].

Types of heating options	Main circuit	Element	Technical specification
SAVHP [11]	Refrigerant circuit	Compressor (I)	Type: hermetic; reciprocating; manufacturer: Tecumseh; model: TFH 4524 F; refrigerant: R-22
		Heat exchanger (II) • Condenser for heating • Evaporator for cooling	Manufacturer: Alfa Laval; model: CB 26–24; capacity: 6.66 kW; heat transfer surface: 0.55 m^2
		Capillary tube (III)	Copper capillary tube; 1.5 m long; inside diameter: 1.5 mm
		Heat exchanger (IV) • Evaporator for heating • Condenser for cooling	Manufacturer: Alfa Laval; model: CB 26–34; capacity: 8.2 kW; heat transfer surface: 0.80 m^2
	Ground coupling circuit	Ground heat exchanger (V)	Vertical-single U-bend type; bore diameter: 105 mm; diameter of U-bends: 32 mm; boring depth: 50 m; material: polyethylene
		Brine circulating pump (VI)	Manufacturer: Marina; type: KPM 50
		Expansion tank (VII)	Manufacturer: Zimmet; type: 541/L
		Solar collector (VIII)	1.82 m^2, flat-type
	Fan-coil circuit	Water circulating pump (IX)	Manufacturer: Marina; type: KPM 50
		Fan-coil unit (X)	Manufacturer: Aldag; type: SAS 28; supply/return temperatures: 56/46 °C
		Small greenhouse (XI)	Net floor area: 11.5 m^2; volume: 28.75 m^3; GRP surface area: 48.51 m^2; indoor/exterior air temperatures 20/6 °C
Wood (pellets) biomass boiler [28]	Lower heating value		17,900 kJ/kg
	Boiler efficiency		88%
	Fuel unit price		100 $CAD/t
Natural gas boiler [28]	Lower heating value		37,000 kJ/m^3
	Boiler efficiency		93%
	Fuel unit price		8.25 $CAD/GJ
	Large greenhouse [27]		Area: 7.5 ha; floor area dimensions: 274 × 274 m^2; height; 4.3 m; covered area: 80,340 m^2; design inside/outside temperatures: 16/7 °C; theoretical heat power requirement: 7.4 MW; actual heat power specified for the 7.5-ha greenhouse: 7.5 MW

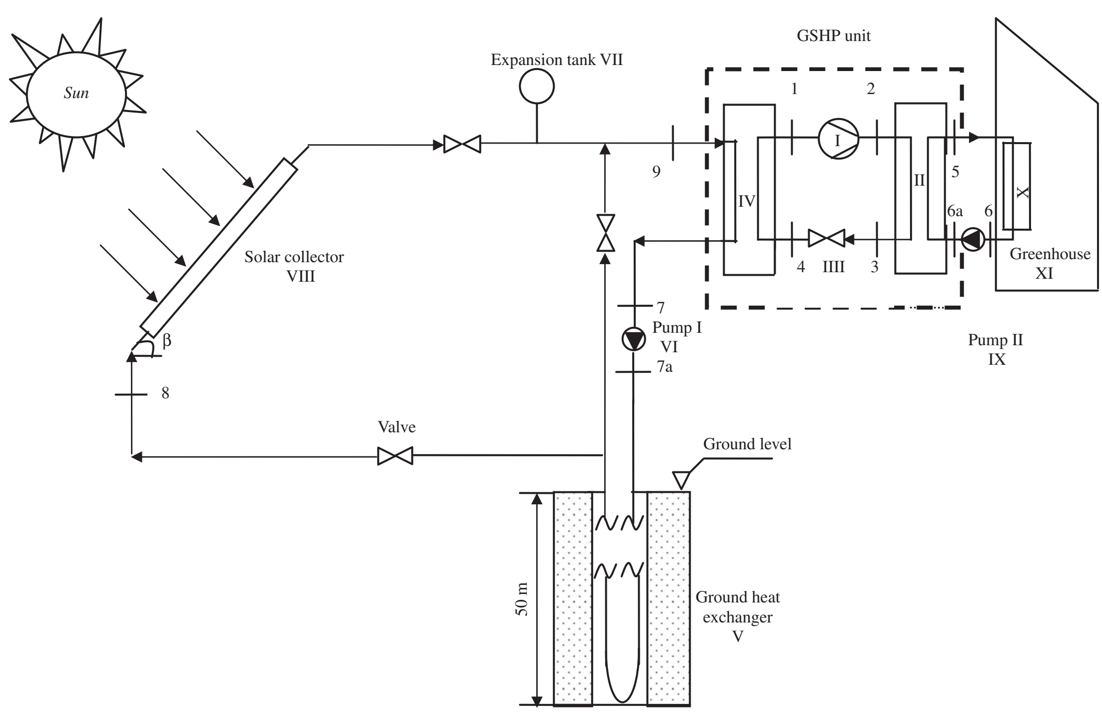


Fig. 1. A schematic diagram of a solar assisted vertical ground source heat pump system for greenhouse heating [11].

$$\dot{Q}''_h = \dot{Q}_h / A_N \quad (3)$$

For the energy source in the primary energy transformation given parameters, F_p and $F_{q,s}$ are the figures of the primary energy factor and the quality factor of the energy source, respectively. F_R is a fraction factor for the environment. In this study, F_p and $F_{q,s}$ are estimated to be 3 and 1 for the heat pump system used in Case 1, respectively. Because a ground heat pump is used for heat generation and its COP is 3.1, so F_R = 2.1 is taken. The heat storage system is not used in this study.

The thermal efficiency of the distribution system is calculated by

$$\eta_{dis} = 0.98 \cdot f_{gp} \cdot f_{ins} \cdot f_{dt} \cdot f_{td} \quad (4)$$

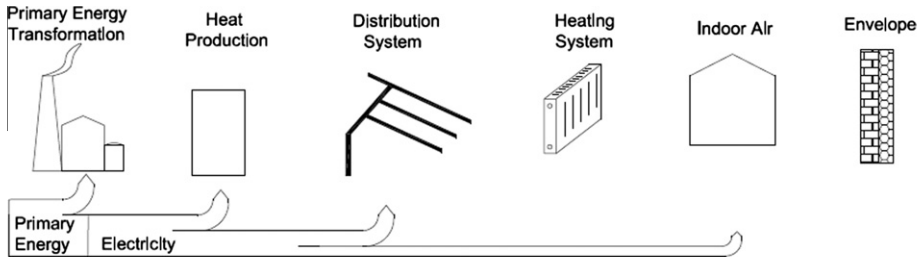


Fig. 2. Energy flows from primary energy transformation to the environment (adopted from Refs. [29,30]).

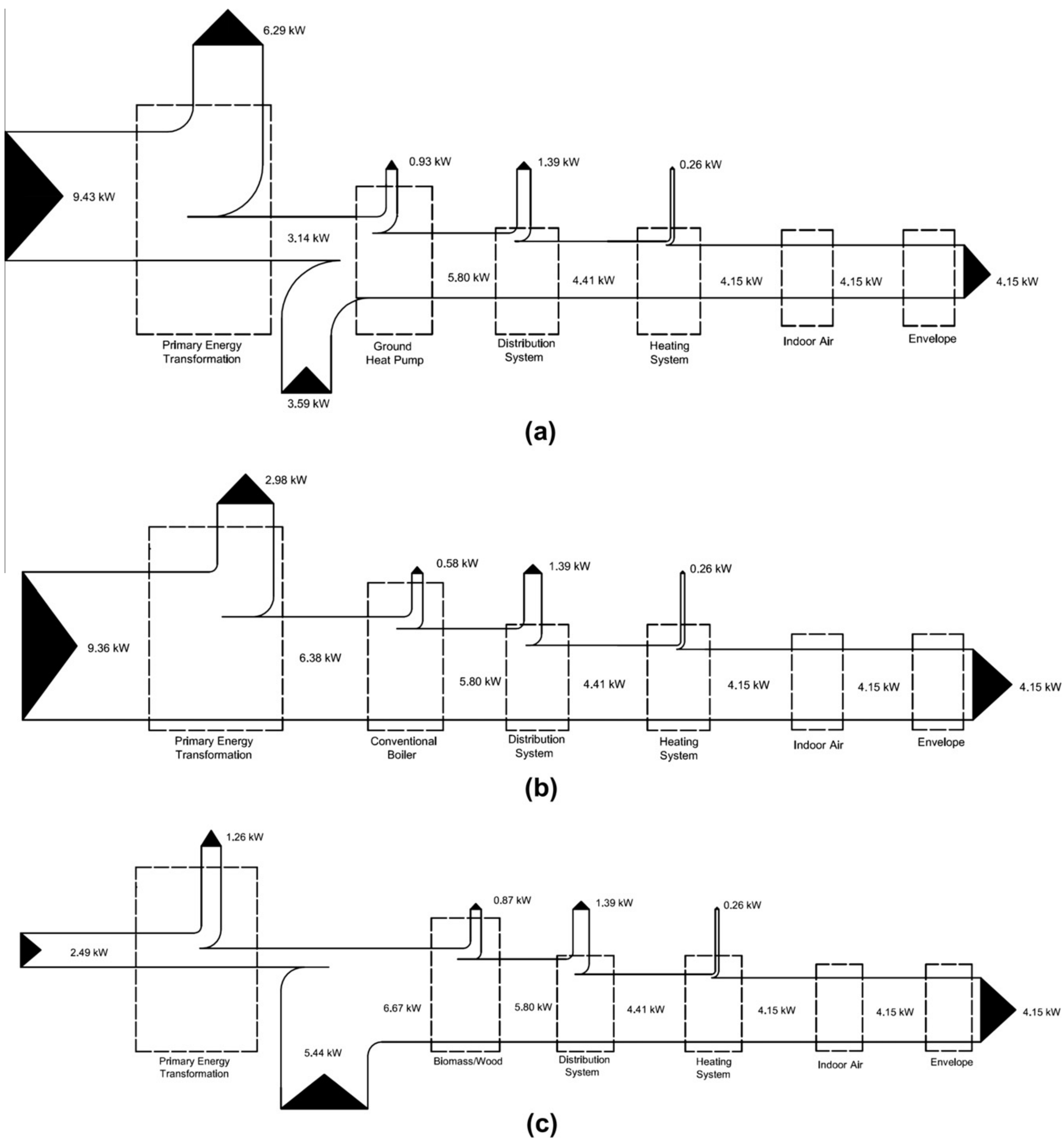


Fig. 3. Energy flow diagram for the SGH (a) ground-source heat pump, (b) natural gas boiler and (c) wood biomass boiler.

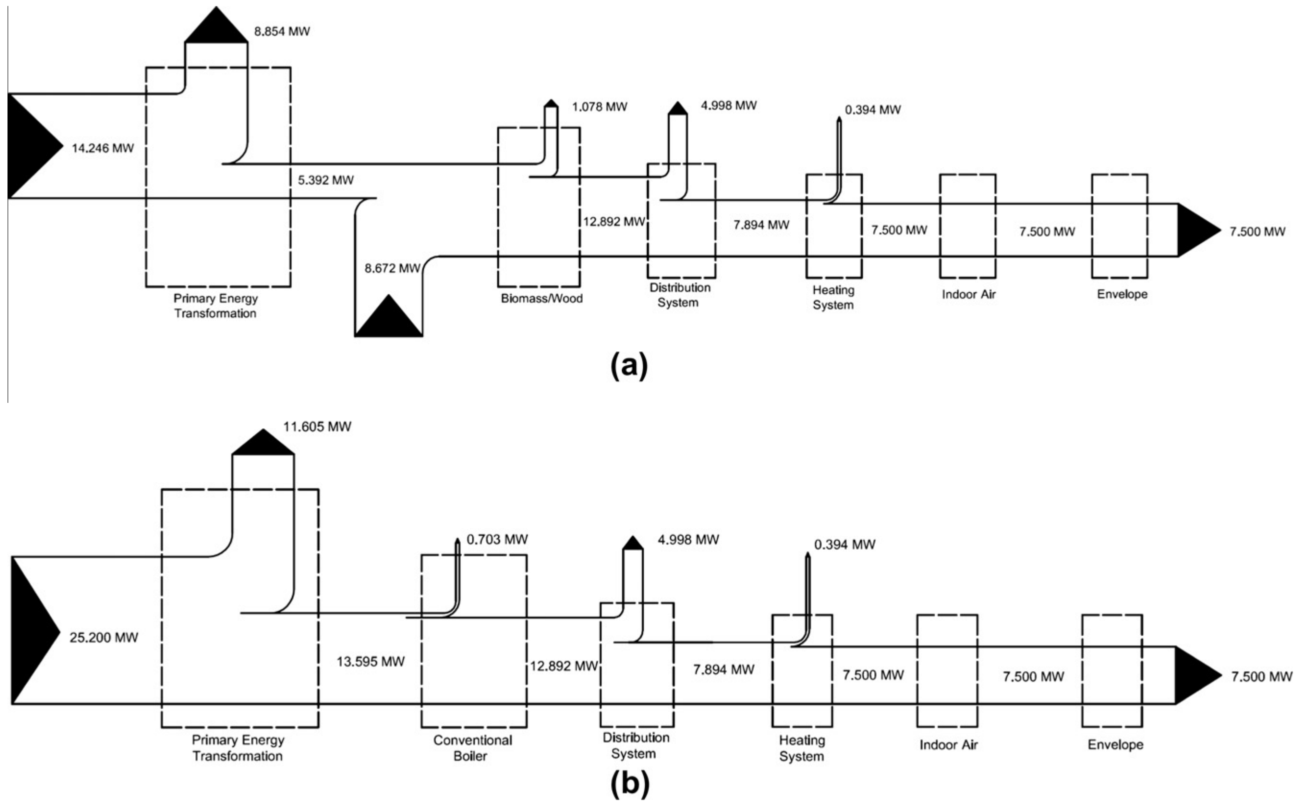


Fig. 4. Energy flow diagrams for the LGH (a) wood biomass boiler and (b) natural gas boiler.

where f_{gp}, f_{ins}, f_{dt} and f_{td} are taken to be 0.9, 1, 0.95 and 0.99 for Case 1, and 1, 1, 0.9 and 1 for Case 2 from Ref. [30].

The auxiliary energy factor $p_{\text{aux,dis}}$ can be obtained from

$$p_{aux,dis} = \frac{\Delta p . \dot{v}}{\eta_{\text{circ}}} \tag{5}$$

where η_{circ} is the electrical efficiency of the circulator. The following calculation results in the pressure difference in the distribution Δp as

$$\Delta p = (1 + N) \cdot R \cdot l_{\max} \cdot A_N + p_{ex} \tag{6}$$

where N is the percentage of equipment resistances with a typical value of 0.3. R is the pressure drop of the pipe, which is assumed to be 0.1 kPa/m. The maximal pipe length of the distribution is given as an area specific value l_{max} with a typical value of 0.25 m/m^2, length per net floor area A_N.

For the average volumetric flow under design conditions, $\dot{v}$ is calculated through

$$\dot{v} = \frac{1}{(1.163.\Delta T_{dis}.0.0036)(s/m^3K)} \tag{7}$$

In the heat distribution system, the fan-coils are used with an efficiency of 0.95.

The quality factor of the indoor air $F_{q,air}$ is calculated by

$$F_{q,air} = 1 - \frac{T_o}{T_i} \tag{8}$$

The exergy load rate can be given by

$$\dot{E}x_{air} = F_{q,air} . \dot{Q}_h \tag{9}$$

The surface temperature of the heater, T_{heat} is estimated using the logarithmic mean temperature of the carrier medium with the inlet, T_{in} and return temperature, T_{ret} of the heating system [33].

$$T_{heat} = \frac{T_{in} - T_{ret}}{\ln\left(\frac{T_{in} - T_i}{T_{ret} - T_i}\right)} 1/2 \cdot + T_i \tag{10}$$

and

$$T'_{heat} = T_{heat} + 273.15\ \text{K} \tag{11}$$

Using this temperature, a new quality factor at the heater surface can be calculated from

$$F_{q,heat} = 1 - \frac{T_{ref}}{T'_{heat}}, \tag{12}$$

The exergy load rate at the heater is

$$\dot{E}x_{heat} = F_{q,heat} \cdot \dot{Q}_h \tag{13}$$

Since the energy efficiency of the distribution system (η_E) is not 100%, an energy load calculation first has to be performed and the heat loss rates have to be calculated as:

$$\dot{Q}_{loss,HS} = \dot{Q}_h \cdot \left(\frac{1}{\eta_{HS}} - 1\right) \tag{14}$$

Keeping the derivation of the exergy demand rate of the heating system as calculated from

$$\Delta\dot{E}x_{HS} = \frac{(\dot{Q}_h + \dot{Q}_{loss,HS})}{(T_{in} - T_{ret})} \left\{ (T_{in} - T_{ret}) - T_{ref} . \ln\left(\frac{T_{in}}{T_{ret}}\right) \right\} \tag{15}$$

The exergy load rate of the heating system is:

$$\dot{E}x_{HS} = \dot{E}x_{heat} + \Delta\dot{E}x_{HS} \tag{16}$$

The heat loss rate of the distribution system results in

$$\dot{Q}_{loss,dis} = (\dot{Q}_h + \dot{Q}_{loss,HS}) \cdot \left(\frac{1}{\eta_{dis}} - 1\right) \tag{17}$$

where η_{dis} is the energy efficiency of the distribution system.

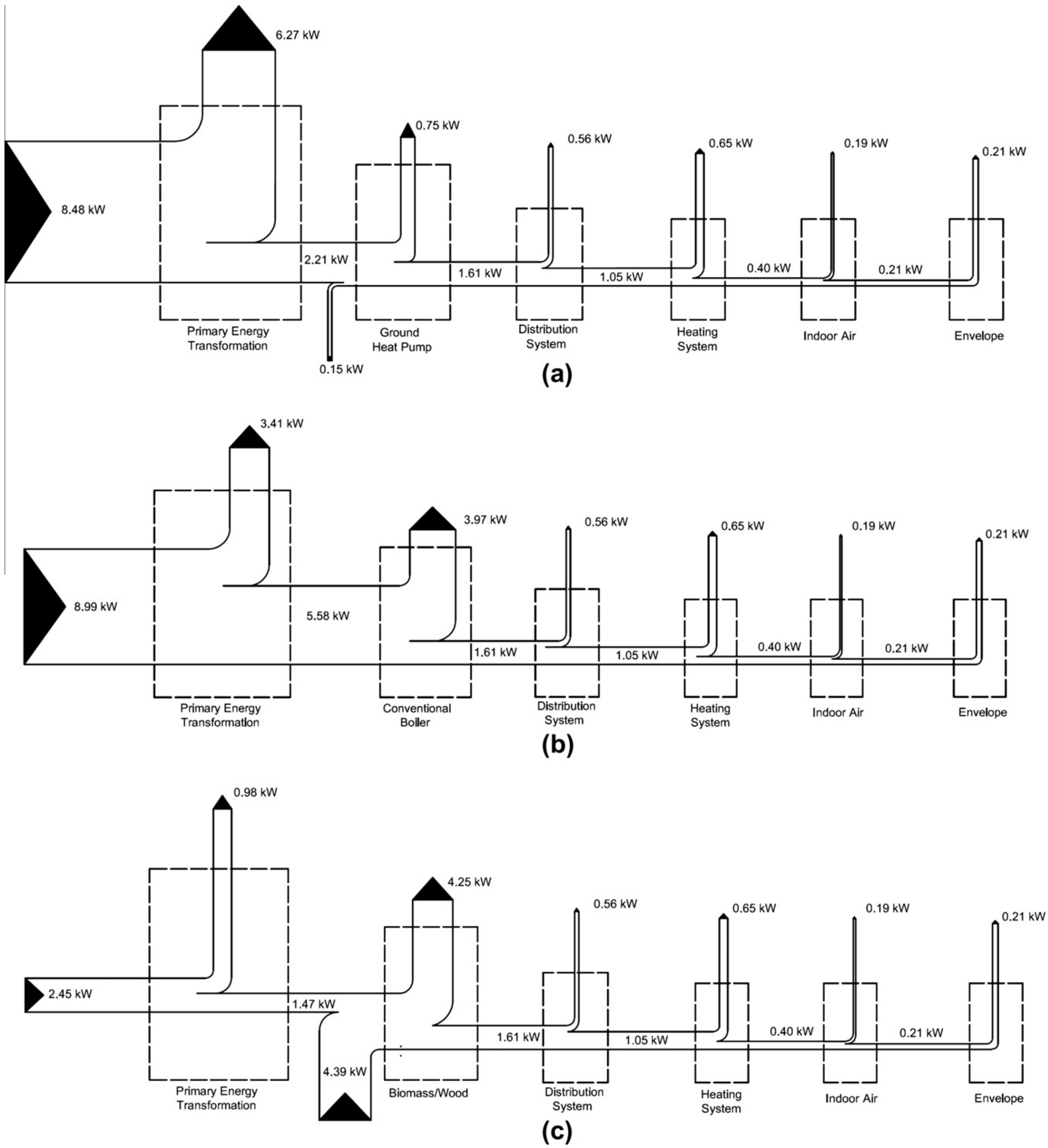


Fig. 5. Exergy flow diagram for the SGH (a) ground-source heat pump, (b) natural gas boiler and (c) wood biomass boiler.

The demand on auxiliary energy or electricity of the distribution system is given by

$$P_{aux,dis} = p_{aux,dis} \cdot (\dot{Q}_h + \dot{Q}_{loss.HS}) \tag{18}$$

Exergy demand rate of the heating system becomes

$$\Delta \dot{E}x_{dis} = \frac{\dot{Q}_{loss,dis}}{\Delta T_{dis}} \left\{ T_{dis} - T_{ref} . \ln \left(\frac{T_{dis}}{T_{dis} - \Delta T_{dis}} \right) \right\} \tag{19}$$

where the inlet temperature of the distribution system is the mean design temperature T_{dis} and the return temperature is the design temperature minus the temperature drop ΔT_{dis} (not: used here as absolute temperatures in K):

The exergy load rate of the distribution system becomes

$$\dot{E}x_{dis} = \dot{E}x_{HS} + \Delta \dot{E}x_{dis} \tag{20}$$

If a seasonal storage is integrated into the system design, some of the required heat is covered by thermal solar power with a certain solar fraction F_S. The required energy to be covered by the generator is

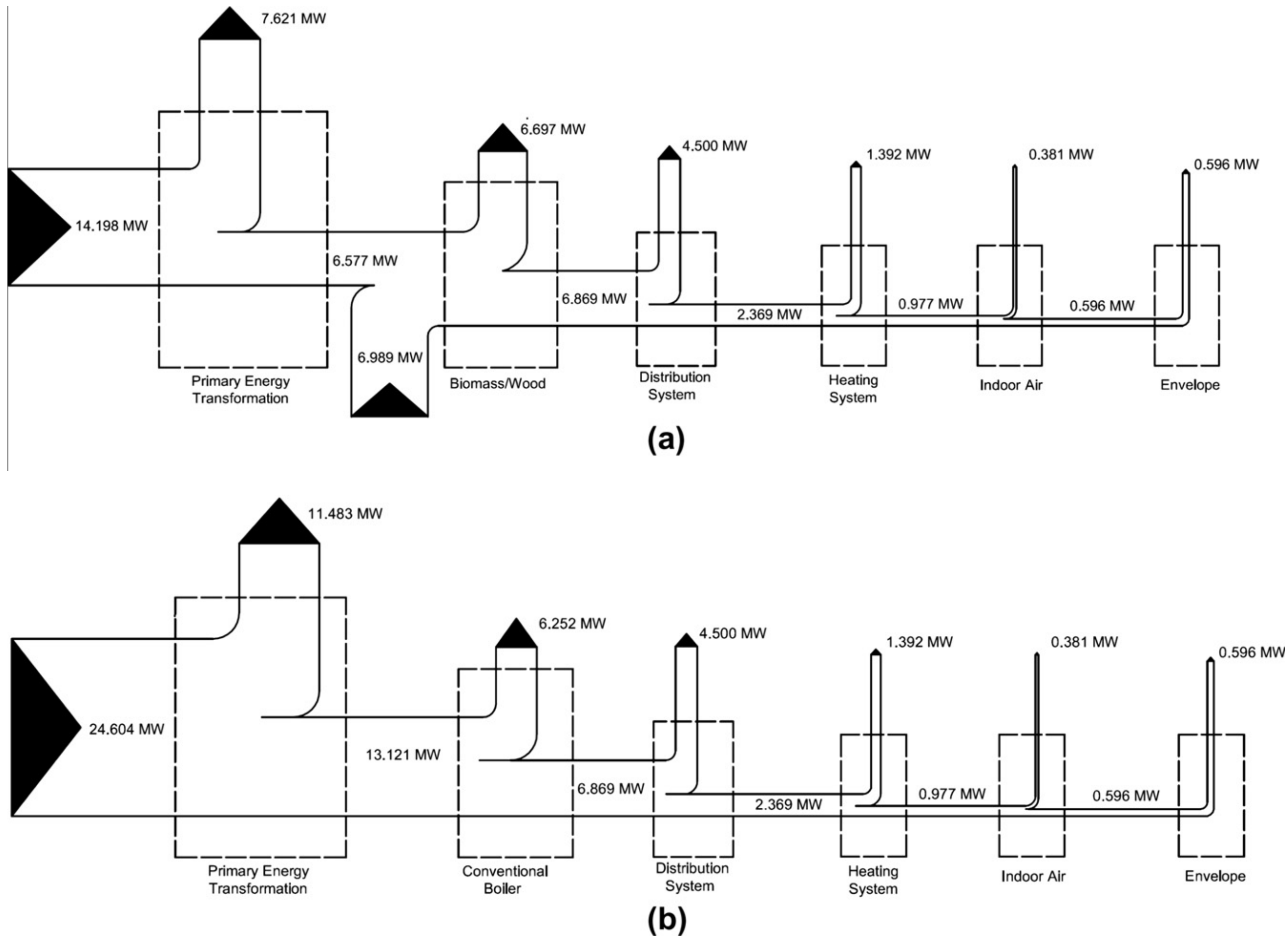


Fig. 6. Exergy flow diagrams for the LGH (a) Wood biomass boiler and (b) Natural gas boiler.

$$\dot{Q}_{Ge} = (\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis}) \cdot (1 - F_S) \cdot \frac{1}{\eta_{Ge}} \tag{21}$$

The demand rate on auxiliary energy of the generation system to drive pumps and fans is:

$$P_{aux,Ge} = p_{aux,Ge} \cdot (\dot{Q}_h + \dot{Q}_{loss,HS} + \dot{Q}_{loss,dis}) \tag{22}$$

The exergy load rate of the generation is calculated through

$$\dot{E}x_{Ge} = \dot{Q}_{Ge} . F_{q,dis} \tag{23}$$

As a second step, the exergy load rate of other greenhouse service appliances, such as lighting, ventilation, are taken into consideration and, in this case, named "plant".

$$\dot{E}x_{\text{plant}} = (P_l + P_V) . F_{q,el} \tag{24}$$

The overall energy and exergy load rates of the greenhouse are expressed in the required primary energy and exergy input rates. For the fossil or non-renewable part of the primary energy, the result becomes

$$\dot{E}_{p,tot} = \dot{Q}_{Ge} \cdot F_P + (P_l + P_V + P_{aux,Ge} + P_{aux,dis} + P_{aux,HS}) \cdot F_{p,el} \tag{25}$$

If the generation utilizes a renewable energy source or extracts heat from the environment, as heat pumps do, the additional renewable energy load rate is:

$$\dot{E}_R = \dot{Q}_{Ge} \cdot F_R + \dot{E}_{env} \tag{26}$$

The total exergy load rate of the greenhouse becomes

$$\dot{E}x_{tot} = \dot{Q}_{Ge} \cdot F_p \cdot F_{q,s} + (P_l + P_V + P_{aux,Ge} + P_{aux,dis} + P_{aux,HS}) \cdot F_{p,el} + \dot{E}_R \cdot F_{q,R} \tag{27}$$

This is a key parameter and can be used for a ranking in a specific value, for comparing greenhouses and their efficiency and quality of exergy utilization, and for evaluating the success of the exergy optimization.

$$\dot{E}x''_{tot} = \frac{\dot{E}x_{tot}}{A_N}, \tag{28}$$

In addition to the energy and exergy efficiencies given above, three more parameters for comparison purposes, namely sustainability index, energetic renewability ratio and exergetic renewability ratio, are studied as follows:

3.1. Exergy efficiency and sustainability index

Sustainable development requires not only that the sustainable supply of clean and affordable energy resources be used, but also the resources should be used efficiently. Exergy methods are very useful tools for improving efficiency, which maximize the benefits and usage of resources and also minimize the undesired effects (such as environmental damage). Exergy analysis can be used to improve the efficiency and sustainability [34].

The relation between exergy efficiency (ψ) and the sustainability index (SI) as given in [35] can be modified to this application:

$$\psi = 1 - \frac{1}{SI} \tag{29}$$

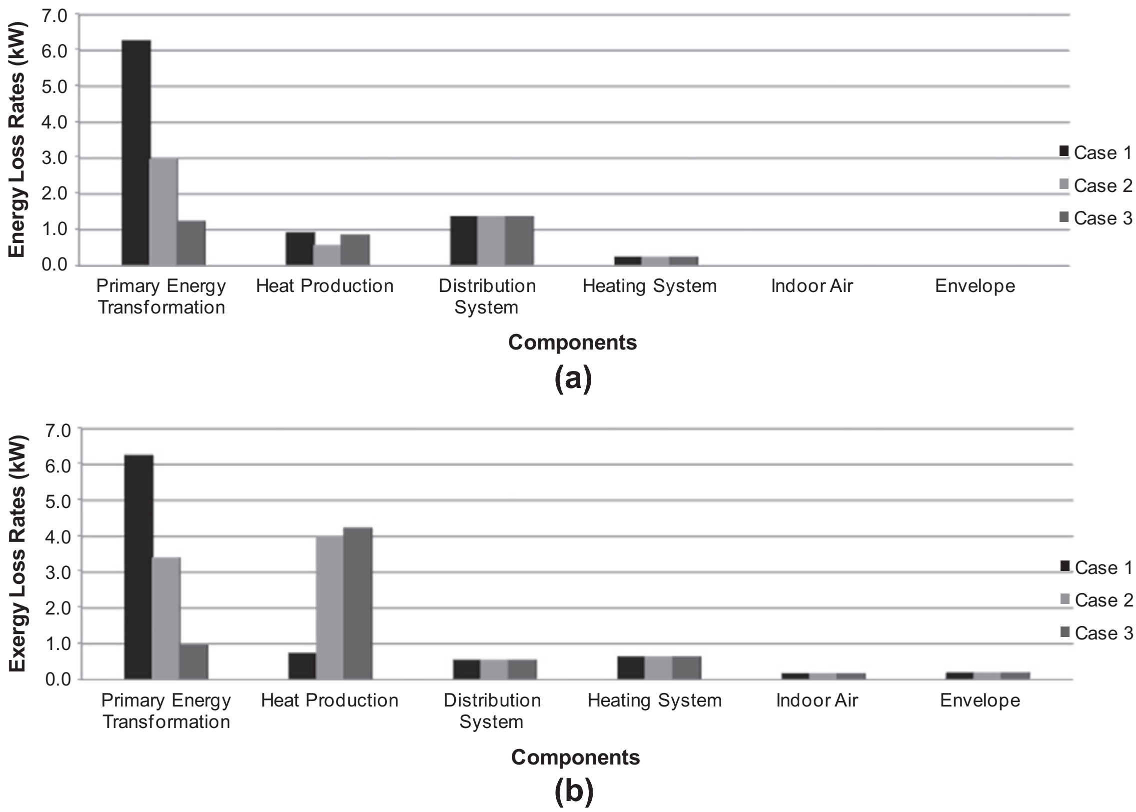


Fig. 7. Variation of energy (a) and exergy (b) loss rates through components for the SGH (Case 1: ground-source heat pump, Case 2: natural gas boiler and Case 3: wood biomass boiler).

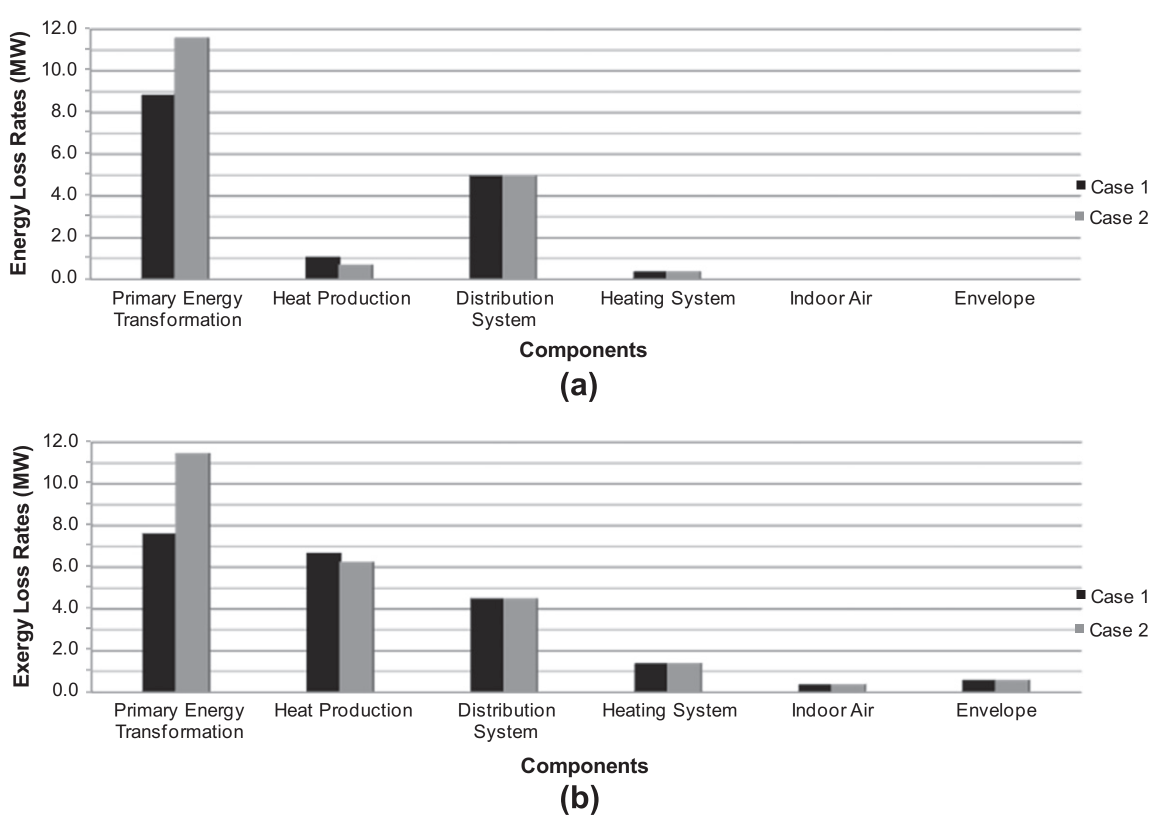


Fig. 8. Variation of energy (a) and exergy (b) loss rates through components for the LGH (Case 1: wood biomass boiler and Case 2: natural gas boiler).

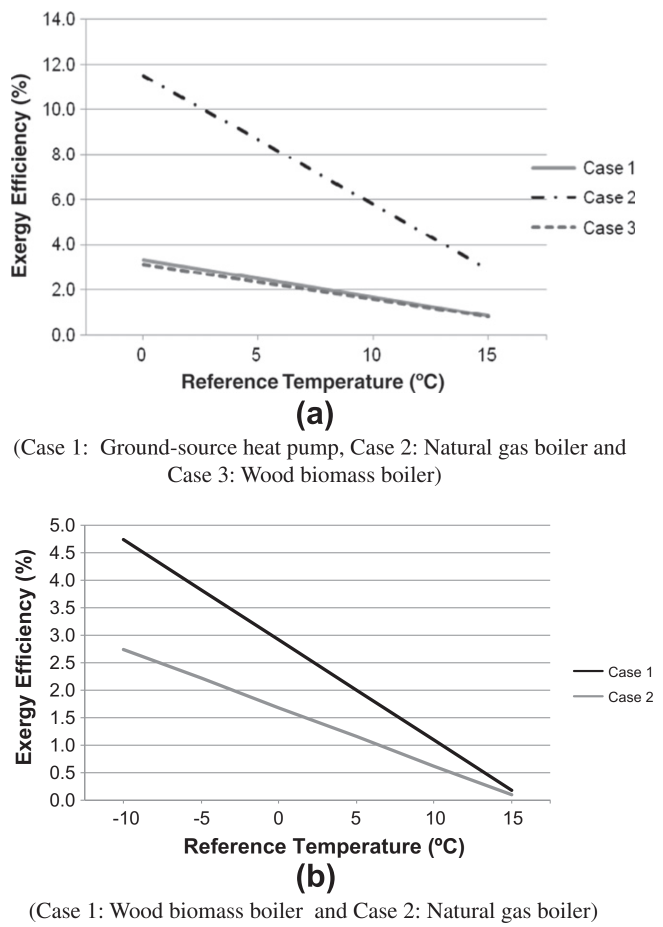


Fig. 9. Variation of overall exergy efficiencies with varying reference state temperatures for (a) SGH and (b) LGH.

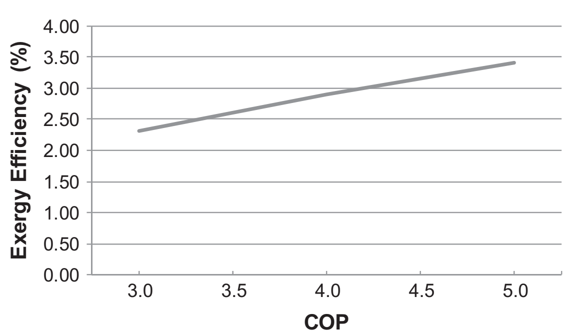


Fig. 10. Variation of overall exergy efficiencies with COP values for the SGH.

which shows how sustainability is affected by changing the exergy efficiency of a process.

3.2. Energetic renewability ratio

The energetic renewability ratio ($R_{R_{En}}$) is defined as ratio of useful renewable energy supplied to the greenhouse to the total energy input to the system [36]:

$$R_{R,En} = \frac{\dot{E}_{usf}}{\dot{E}_{tot}} \tag{30}$$

3.3. Exergetic renewability ratio

The exergetic renewability ratio ($R_{R_{Ex}}$) is defined as ratio of useful renewable exergy supplied to the greenhouse to the total exergy input to the system [36]:

$$R_{R,Ex} = \frac{\dot{E}x_{usf}}{\dot{E}x_{tot}} \tag{31}$$

4. Results and discussion

The process begins with the power plant, through the production of heat, via a distribution system, to the heating system and from there, via the greenhouse air, across the greenhouse envelope to the outside environment. For the small greenhouse (SGH) system, project data and boundary conditions are as follows: volume is 28.75 m^3, net floor area is 11.5 m^2, while indoor and exterior air temperatures are 20 °C and, 6 °C, respectively. For the large greenhouse (LGH) system, project data and boundary conditions are: volume is 322,500 m^3, net floor area is 75,000 m^2, while indoor and exterior air temperatures are 16 °C and, −7 °C, respectively. The values of η_{HS} and η_{dis} are assumed to be 0.95 and 0.82 for biomass/wood-fired, ground-source heat pump and NG-fired heating systems, respectively, while those of η_{dis} are 0.88, 3.10 and 0.93

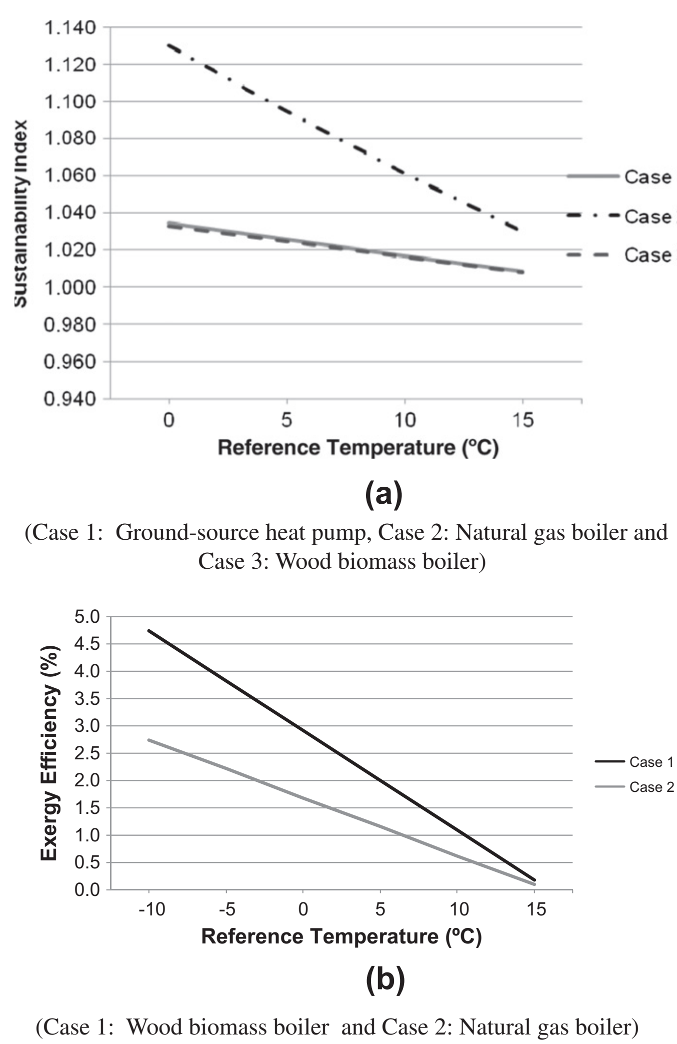


Fig. 11. Sustainability index values for (a) SGH and (b) LGH.

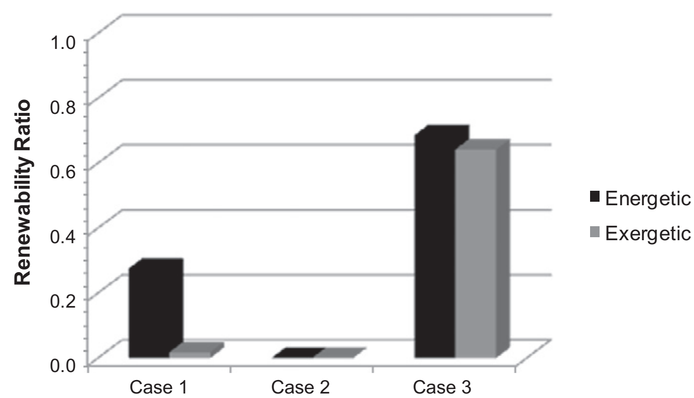
and those of $F_{q,el}$ are 1.0, 0.9 and 1.0 for the same systems considered, respectively. The value of F_s is taken to be zero.

In this study, both the actual data and the data taken from the literature are utilized to analyze and evaluate the performance of two types of greenhouses considered. The heat losses are based on the measured values from the author's common studies and the literature reported by other investigators. In this regard, determination of the heat losses, which is the first step in this analysis, may be done in more detail using the relevant relations given in the literature. According to the data utilized, the heat demand rates are 4.15 kW and 7.5 MW for the SGH and LGH, while their specific heat demand rates calculated from Eq. (3) are 360.87 W/m^2 and 100 W/m^2, respectively.

Figs. 3 and 4 show energy flow diagrams for the SGH and LGH, respectively. For the considered cases, the SGH system requires primary energy rates of 13.02 kW, 9.36 kW and 7.93 kW in order to supply a total of 4.15 kW to the SGH. On the other hand, the primary energy rates for the LGH system of Cases 1 and 2 are calculated as 22.918 MW and 25.200 MW in order to supply a total of 7.500 MW to the LGH. For both of the SGH and LGH, the highest amounts of heat loss rates occur in the primary energy transformation except Case 3 of the SGH. In the heat production section of the SGH system for Cases 1 and 3 and the LGH system for Case 1, an increase in the energy flow is due to the ground heat pump and biomass/wood, which produce 6.73 kW and 6.67 kW for the SGH system and 14.064 MW for the LGH system, respectively. The explanation for this increase is the amount of renewable environmental heat included in this section. The total exergy demand rate is determined based on the methodology as followed in the energy demand calculation, but using exergy analysis approach. Similarly, the same operating conditions for each component of the SGH and LGH systems in themselves are considered.

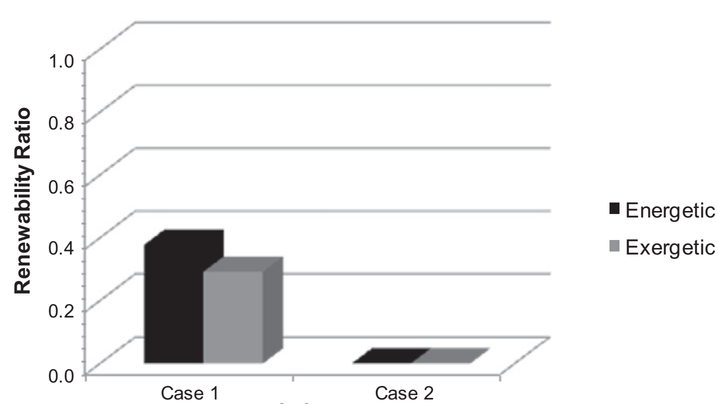
The largest exergy demand rates are calculated for the primary energy transformation of Case 2 for the SGH as 8.99 kW and Case 2 for the LGH as 24.604 MW. Also, as can be seen in Figs. 5 and 6, the smallest exergy demand rate is 6.88 kW for the SGH system for Case 2 and 21.187 MW for the LGH system for Case 1.

The variations of energy and exergy loss rates through components for the both systems are shown in Figs. 7 and 8. Largest The largest energy and exergy loss rates take place in the primary energy transformation and heat production, as expected. On the other hand, it is clear from Figs. 5 and 6 that exergy is consumed continually in each component for all cases. While the flow of energy leaves the building envelope, there is still a remarkable amount of energy left, but this is not true for exergy. At the reference environment conditions, exergy has no potential of doing work; so all exergy has been consumed. The exergy flow on the right side of the diagram is required to be zero. It is also investigated how the exergy efficiencies for the studied cases for the SGH and LGH systems considered here vary with the reference temperature. Apparently, Fig. 9 indicates the influence of changing the reference temperature on exergy efficiencies. In this figure, the highest exergy efficiency values are obtained for Cases 2 and 1 for the SGH and LGH systems, respectively. So, the exergy efficiency of the SGH system for Case 2 decreases from 11.55% to 2.90% with the reference environment temperature increasing from 0 to 15 °C and



(a)

(Case 1: Ground-source heat pump, Case 2: Natural gas boiler and Case 3: Wood biomass boiler)



(b)

(Case 1: Wood biomass boiler and Case 2: Natural gas boiler)

Fig. 12. Renewability ratio values for (a) SGH and (b) LGH.

the exergy efficiency of LGH system for Case 1 decreases from 4.75% to 0.18% with the reference environment temperature increasing from −10 to 15 °C. Also, it is clear here that exergy efficiencies decrease as the reference environment temperature increases. The reference environment temperature is a state of a system, in which it is at the equilibrium with its surroundings. Fig. 10 illustrates the effects of the COP on the exergy efficiency of the system. It is obviously seen that the exergy efficiency increases with the COP values. By comparison, Caliskan and Hepbasli [23] reported in a tabulated form that the whole exergy efficiency in the heating of various buildings with floor areas ranging from 35 to 2202 m^2 varied between 0.40% and 9.5%, mostly being over 3.5%. The overall exergy efficiency values of the greenhouse systems studied are in the range of 0.18–11.5% at dead state temperatures varying from -10 to 15 °C.

Using Eq. (29), the sustainability index values for the SGH and LGH systems are calculated and illustrated in Fig. 11, which includes the effects of varying reference temperatures on the sustainability index values. As can be seen from this figure, these values of the all cases decrease with the increase in the reference environment temperature.

Furthermore, using Eqs. (30) and (31), both energetic and exergetic renewability ratios for all cases studied are calculated and indicated in Fig. 12. In the SGH system, they are obtained to be 0.28, 0 and 0.69, and 0.02, 0 and 0.64 for ground-source heat pump, natural gas boiler and wood biomass boiler, respectively. In the LGH system, they are found to be 0.39 and 0, and 0.29 and 0 for wood biomass and natural gas boilers, respectively. It may be concluded that the most sustainable system becomes the wood biomass boiler among the cases studied.

5. Conclusions

This paper has undertaken a study to conduct both energy exergy analyses of three heating options for greenhouse heating, namely (i) a solar assisted vertical ground-source heat pump, (ii) a wood biomass boiler, and (iii) a natural gas boiler, driven by renewable and fossil-fuel sources for a greenhouse and to compare their performances through both energy and exergy efficiencies.

Some concluding remarks from this study are listed as follows:

- The overall exergy efficiency values for Cases 1–3 of the solar assisted vertical ground-source heat pump heating system decrease from 3.33% to 0.83%, 11.5% to 2.90% and 3.15% to 0.79% at varying reference state temperatures of 0–15 °C while those for Cases 1 and 2 of the large greenhouse system decrease from 2.74% to 0.11% and 4.75–0.18% at varying reference state temperatures of −10 to 15 °C.
- The sustainability index values for Cases 1–3 of the small greenhouse system vary between 1.034–1.008, 1.13–1.03 and 1.033–1.008 at varying reference state temperatures of 0–15 °C, while those for Cases 1 and 2 of the large greenhouse system range from 1.028 to 1.006 and 1.050–1.011 at varying reference state temperatures of −10 to 15 °C.
- The energetic renewability ratio values for Cases 1 and 3 of the small greenhouse system are calculated to be 0.28 and 0.69 while the exergetic renewability ratio values for those 0.02 and 0.64, respectively.
- The energetic and exergetic renewability ratio values for Case 1 of the large greenhouse system are obtained to be 0.39 and 0.29, respectively.
- For a future work, it is recommended to conduct a detailed cost accounting and exergoeconomic analysis (which is a combination of exergy and economics) for various types of greenhouse heating systems for comparison purposes.

Acknowledgements

The author is grateful to the three reviewers as well as Editor-in-Chief Prof. J. Yan and Associate Editor Prof. SK Chou due to a quick review process and their valuable comments, which have been utilized in improving the quality of the paper. He also likes to take the opportunity to thank both Dr. Dietrich Schmidt and Prof. Dr. Masanori Shukuya for their kind invitations to being a member in LowEx.Net: *Network of International Society for Low Exergy Systems in Buildings* (http://www.lowex.net/).

References

[1] Lund H, Ostergaard PA, Stadler I. Towards 100% renewable energy systems. Appl Energy 2011;88:419–21.
[2] Mathiesen BV, Lund H, Karlsson K. 100% Renewable energy systems, climate mitigation and economic growth. Appl Energy 2011;88:488–501.
[3] Annex 49. Energy conservation in buildings and community systems—low exergy systems for high performance buildings and communities. <http://www.annex49.com> [accessed 05.02.11].
[4] Schmidt D. Low exergy systems for high-performance buildings and communities. Energy Build 2009;41:331–6.
[5] Annex 37. Energy conservation in buildings and community systems – low exergy systems for heating and cooling of buildings. <http://virtual.vtt.fi/annex37/> [accessed 05.02.11].
[6] Mohammadi A, Omid M. Economical analysis and relation between energy inputs and yield of greenhouse cucumber production in Iran. Appl Energy 2010;87:191–6.
[7] Chou SK, Chua KJ, Ho JC, Ooi CL. On the study of an energy-efficient greenhouse for heating, cooling and dehumidification applications. Appl Energy 2004;77:355–73.
[8] Chua KJ, Chou SK, Yang WM. Advances in heat pump systems: a review. Appl Energy 2010;87(12):3611–24.
[9] Ozyurt O, Ekinci DA. Experimental study of vertical ground-source heat pump performance evaluation for cold climate in Turkey. Appl Energy 2011;88:1257–65.
[10] Lienau FJ, Lunis BC. Greenhouses. Geothermal direct use engineering and design guidebook. USA: Oregon Institute of Technology; 1990 [chapter 14].
[11] Ozgener O, Hepbasli A. Experimental investigation of the performance of a solar assisted ground-source heat pump system for greenhouse heating. Int J Energy Res 2005;29(2):217–31.
[12] Leskinen M, Simonson C, Virtanen M. Low exergy sources for heating and cooling & IEA Annex 37. IEA energy conservation in buildings and community systems technical presentations, Zurich. <virtual.vtt.fi/annex37/technical%20day%20report_zurich.pdf> [accessed 10.02.11 and 12.07.2000].
[13] Kelly S, Tsatsaronis G, Morosuk T. Advanced exergetic analysis: approaches for splitting the energy destruction into endogenous and exogenous parts. Energy 2009;34:384–91.
[14] Schmidt D, Juusela MA. Low-exergy systems for heating and cooling of buildings., in: Proceedings of the 21st conference on passive and low energy architecture, Eindhoven, The Netherlands; 2004.
[15] LowEx Network. Lowex guide book. Low exergy systems for heating and cooling of buildings guide book. Examples of LowEx buildings. <http://www.lowex.net/guidebook/index.htm> [accessed 13.02.11].
[16] IEA, Low exergy heating and cooling of buildings – Annex 37. <http://www.vtt.fi/rte/projects/annex37/Index.htm> [19.05.008].
[17] Balta MT, Kalinci Y, Hepbasli A. Evaluating a low exergy heating system from the power plant through the heat pump to the building envelope. Energy Build 2008;40(10):1799–804.
[18] Kalinci Y, Balta TM, Hepbasli A. Performance assessment of a geothermally heated building. Energy Policy 2009;37(4):1502–8.
[19] Shukuya M. Exergy concept and its application to the built environment. Build Environ 2009;44(7):1545–50.
[20] Torío H, Angelotti A, Schmidt D. Exergy analysis of renewable energy-based climatisation systems for buildings: a critical view. Energy Build 2009;41(3):248–71.
[21] Yildiz A, Güngör A. Energy and exergy analyses of space heating in buildings. Appl Energy 2009;86(10):1939–48.
[22] Dovjak M, Shukuya M, Olesen BW, Krainer A. Analysis on exergy consumption patterns for space heating in Slovenian buildings. Energy Policy 2010;38(6):2998–3007.
[23] Caliskan H, Hepbasli A. Energy and exergy analyses of ice rink buildings at varying reference temperatures. Energy Build 2010;42(9):1418–25.
[24] Yucer CT, Hepbasli A. Thermodynamic analysis of a building using exergy analysis method. Energy Build 2011;43(2–3):542–8.
[25] Hepbasli A (Principal Investigator), Ozgener O, Hancioglu E (Co-investigators). Greenhouse heating and drying applications using a ground-heat pump, project no.: 2003-GEE-009. The Research Fund of Ege University; 2006 [in Turkish].

[26] Ozgener O, Hepbasli A. Performance analysis of a solar assisted ground-source heat pump system for greenhouse heating: an experimental study. Build Environ 2005;40(8):1040–50.
[27] Chau J, Sowlati T, Sokhansanj S, Preto F, Melin S, Xi B. Techno-economic analysis of wood biomass boilers for the greenhouse industry. Appl Energy 2009;86:364–71.
[28] Chau J, Sowlati T, Sokhansanj S, Preto F, Melin S, Bi X. Economic sensitivity of wood biomass utilization for greenhouse heating application. Appl Energy 2009;86:616–21.
[29] Balta MT, Dincer I, Hepbasli A. Performance and sustainability assessment of energy options for building HVAC applications. Energy Build 2010;42(8):1320–8.
[30] Schmidt D. Design of low exergy buildings-method and a pre-design tool. Int J Low Energy Sustain Build 2003;3:1–47.
[31] LowEx. LowEx.Net. Network of international society for low exergy systems in buildings. <http://www.lowex.org> [accessed 18.02.11].
[32] The Canada Plan Service. Greenhouse heating requirements. Plan M-6701. <http://www.cps.gov.on.ca/english/plans/E6000/6701/M-6701L.pdf> [accessed 25.02.11].
[33] Moran MJ, Shapiro HN. Fundamentals of engineering thermodynamics. 3rd ed. New York: John Wiley and Sons; 1998.
[34] Cornelissen RL. Thermodynamics and sustainable development. Ph.D. Thesis, University of Twente; 1997.
[35] Rosen MA, Dincer I, Kanoglu M. Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 2008;36:128–37.
[36] Coskun C, Oktay Z, Dincer I. New energy and exergy parameters for geothermal district heating systems. Appl Therm Eng 2009;29:2235–42.