EXERGY ANALYSIS OF HVAC SYSTEMS FOR A HOUSE IN MONTREAL

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ABSTRACT

This paper presents the integrated energy, entropy and exergy (EEE) analysis of several design alternatives of the HVAC system of a house located in Montreal, for both peak design conditions and annual operating conditions. The results show that the HVAC system using electric baseboard heater and separate electric air ventilation heater has the lowest exergy efficiencies of 7.4% and 4.1% respectively under the above two conditions, while its energy efficiencies are 64.2% and 61.6% respectively under the same conditions. The HVAC system with the highest exergy efficiency of 23.2% (at peak design conditions) and 10.9% (at annual operating conditions) is composed of: radiant floor heating system; ground source heat pump; air-to-air heat exchanger; earth tube heat exchanger; gas-fired DHW heater.

INTRODUCTION

To improve the energy performance of buildings, effective analysis tools and assessment indicators appears to be essential. Leskinen et al. [1] stated that one important task of IEA Annex 37 is the development of a comprehensive set of tools to enable the assessment of low exergy technologies, components and systems. With respect to HVAC system, which contributes to a major fraction of the building energy use and CO_2 emissions, the integrated energy, entropy and exergy (EEE) analysis is an appropriate tool to assess and evaluate its performance.

The energy performance of HVAC systems is usually evaluated based on the first law of thermodynamics. However, compared to energy analysis, the exergy analysis can better and accurately show the location of inefficiencies. The results from exergy analysis can also be used to assess and optimize the performance of HVAC systems. In addition, integration of energy, entropy and exergy analysis can present a whole picture of the system performance. A number of applications of exergy analysis in HVAC system have shown its effectiveness. Kanoglu et al. [2] analyzed an experimental open-cycle desiccant cooling system and showed that the desiccant wheel has the greatest percentage of total exergy destruction followed by the heating system. Ren et al. [3] evaluated the performance of evaporative cooling schemes and showed that the regenerative evaporative cooling has the best performance, and the effectiveness of indirect evaporative heat exchange has great importance in improving the exergy efficiency of regenerative scheme. Asada and Takeda [4] found that the ceiling radiant cooling system with well water is not exergy efficient because of its relatively large electricity consumption by pumps. Badescu [5] found that in a vapor compression heat pump, most exergy losses occur during the compression and condensation process. Rosen et al [6] expressed the opinion that one major weakness in the building energy analysis is the lack of using the second-law analysis.

Renewable energy sources and energy efficient technologies may be utilized to improve the effectiveness of energy use in HVAC system. For a specific project, the selection of renewable energy sources and energy efficient technologies is influenced by many factors, such as local climate, building location, hours of operation, people's habits and cost of energy sources.

In this paper, the integrated energy, entropy and exergy (EEE) analysis is first reviewed. Several design alternatives of the HVAC system for a residential building are then evaluated by using the integrated EEE analysis.

INTEGRATED ENERGY, ENTROPY, AND EXERGY ANALYSIS

Exergy is defined as the maximum useful work that could be obtained from a system at a given state with respect to a reference environment (dead state) [7]. In a process or a system, the total amount of exergy is not conserved but destroyed due to internal irreversibilities.

In a thermodynamic system, exergy can be transferred to or from a system in three forms: heat, work and mass flow, which are recognized at the system boundaries. The exergy transfer by heat $\dot{X}_{heat}$ is expressed as [7]:

$$\dot{X}_{heat} = \left(1 - \frac{T_0}{T}\right)\dot{Q} \qquad \text{(kW)} \qquad (1)$$

Where:

$\dot{Q}$ = rate of heat transfer crossing the system boundaries, kW;

T_o = environment temperature, K;

T = temperature of heat source, K.

In the case of mechanical work or electricity crossing the system boundaries, exergy transfer $\dot{X}_{work}$ (kW) equals the electricity or mechanical work itself $\dot{W}$ (kW).

In the case of mass flow crossing the system boundaries, exergy transfer by mass $\dot{X}_{mass}$ is:

$$\dot{X}_{mass} = \dot{m}x \qquad \text{(kW)} \qquad (2)$$

Where:

$\dot{m}$ = mass flow rate crossing the system boundaries, kg/s;

x = exergy per unit mass, kJ/kg.

For a flow stream, the unit mass exergy can be expressed as:

$$x = (h - h_0) - T_0(s - s_0) \quad \text{(kJ/kg)} \qquad (3)$$

The exergy change of a flow stream is [6]:

$$\Delta x = x_2 - x_1 = (h_2 - h_1) - T_0(s_2 - s_1) \text{(kJ/kg)} \qquad (4)$$

Where:

T =temperature, K;

h =enthalpy, kJ/kg;

s =entropy kJ/kg·K.

The subscript "0" indicates the environmental dead state and subscripts "1" and "2"indicate different states of the flow stream.

For the steady-state flow process, there is no storage of energy, entropy as well as exergy within the system. The energy balance equation is:

$$\dot{E}_{in} = \dot{E}_{out} \qquad \text{(kW)} \qquad (5)$$

The entropy balance equation is:

$$\dot{S}_{in} + \dot{S}_{generated} = \dot{S}_{out} \qquad \text{(kW/K)} \qquad (6)$$

The exergy balance equation is:

$$\dot{X}_{in} = \dot{X}_{destroyed} + \dot{X}_{out} \qquad \text{(kW)} \qquad (7)$$

Where the subscript "in" indicates the flow (energy flow, entropy flow or exergy flow) entering the system and the subscript "out" indicates the flow leaving the system.

Exergy destruction $\dot{X}_{destroyed}$ in a process is the product of entropy generation $\dot{S}_{generated}$ in the same process and the reference environment temperature T_0:

$$\dot{X}_{destroyed} = T_0\dot{S}_{generated} \qquad \text{(kW)} \qquad (8)$$

Wepfer et al. [8] stated that for a system, such as a HVAC system, the steady-flow exergy balance can also be expressed as:

$$\dot{X}_{supplied} = \dot{X}_{useful} + \dot{X}_{destroyed} + \dot{X}_{lost} \quad \text{(kW)} \quad (9)$$

The exergy supplied to the system is partially destroyed inside the system due to the irreversibilities, partially delivered to the outside with the effluents and partially used by the system.

The energy efficiency of a HVAC system is defined as:

$$\eta_1 = \frac{\dot{E}_{useful}}{\dot{E}_{supplied}} \qquad (10)$$

The exergy efficiency, which provides the realistic measure of performance of engineering system [7], can be expressed in the following forms [8]:

$$\eta_2 = \frac{\dot{X}_{useful}}{\dot{X}_{supplied}} \qquad (11)$$

$$\eta_2 = 1 - \frac{\dot{X}_{destroyed} + \dot{X}_{lost}}{\dot{X}_{supplied}} \qquad (12)$$

In order to improve the exergy efficiency η_2, the amount of exergy destroyed inside a system plus the amount lost through the effluents should be reduced.

CASE STUDY

A house located in Montreal with the total floor area of 310 m^2 is used as a case study. The peak and hourly heating loads used in this study were obtained by using the BLAST program [9].

In Quebec, the contribution of energy sources to the off-site electricity generation is [10]: electricity from fossil fuel: 2.2%; electricity from nuclear power: 1.1%; hydro-electricity: 96.7%. The following assumptions are used about the overall energy efficiency of the power plant: fossil fuel power plant: 37% [11]; nuclear power plant: 30% [11]; hydro power plant (electricity output divided by the kinetic energy of the water): 80% [12]. The transmission efficiency of electricity is 86% [13]. The energy, entropy and exergy analysis of the extraction, transportation and distribution of natural gas are not included in this paper. Therefore, the reader should interpret the results in the light of this assumption.

The objective of the HVAC system design is to integrate the space heating, ventilation, domestic hot water (DHW) heating and renewable energies in a way to improve the performance of the HVAC system while satisfying the requirement of indoor comfort. The following energy efficient technologies are used: earth tube heat exchanger, air-to-air heat exchanger, radiant heating floor, ground source heat pump (GSHP), and air source heat pump (ASHP).

Several design alternatives are selected:

1. Heating: electric baseboard heaters.

   Ventilation: electric air heater.

   DHW: electric water heater.
2. Heating: electric baseboard heaters.

   Ventilation: electric air heater and air-to-air heat exchanger.

   DHW: electric water heater.
3. Heating: electric baseboard heaters.

   Ventilation: electric air heater, air-to-air heat exchanger and earth tube heat exchanger.

   DHW: electric water heater.
4. Heating: hot water baseboard heaters with gas-fired boiler.

   Ventilation: hot water air heater, air-to-air heat exchanger, and earth tube heat exchanger.

   DHW: heat exchanger with gas-fired boiler.
5. Heating: hot water baseboard heaters with gas-fired boiler with economizer.

   Ventilation: hot water air heater, air-to-air heat exchanger and earth tube heat exchanger.

   DHW: heat exchanger with gas-fired boiler with economizer.
6. Heating: forced air system with hot water heating coil and gas-fired boiler.

   Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

   DHW: heat exchanger with gas-fired boiler.
7. Heating: forced air system with hot water heating coil and gas-fired boiler with economizer.

   Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

   DHW: heat exchanger with gas-fired boiler with economizer.
8. Heating: forced air system with electric air heater.

   Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

   DHW: electric water heater.
9. Heating: radiant heating floor with GSHP.

   Ventilation: hot water air heater, air-to-air heat exchanger and earth tube heat exchanger.

   DHW: GSHP and electric water heater.
10. Heating: radiant heating floor with GSHP.

    Ventilation: hot water air heater, air-to-air heat exchanger and earth tube heat changer.

    DHW: GSHP and gas-fired water heater.
11. Heating: forced air system with electric air heater and GSHP.

    Ventilation: hot water air heater, electric air heater, air-to-air heat exchanger and earth tube heat exchanger.

    DHW: GSHP and electric water heater.
12. Heating: forced air system with hot water heating coil, gas-fired boiler and GSHP.

    Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

    DHW: GSHP and gas-fired boiler.
13. Heating: forced air system with hot water heating coil, ASHP and electric air heater.

    Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

    DHW: ASHP and electric water heater.
14. Heating: forced air system with hot water heating coil, gas-fired boiler and ASHP.

    Ventilation: air-to-air heat exchanger and earth tube heat exchanger.

DHW: ASHP and gas-fired boiler.

15. Heating: radiant floor with electric boiler.

Ventilation: electric air heater, air-to-air heat exchanger and earth tube heat exchanger.

DHW: electric water heater.

16. Heating: radiant floor with gas-fired boiler.

Ventilation: hot water air heater, air-to-air heat exchanger and earth tube heat exchanger.

DHW: heat exchanger with gas-fired boiler.

17. Heating: radiant heating floor with gas-fired boiler with economizer.

Ventilation: hot water air heater, air-to-air heat exchanger and earth tube heat exchanger.

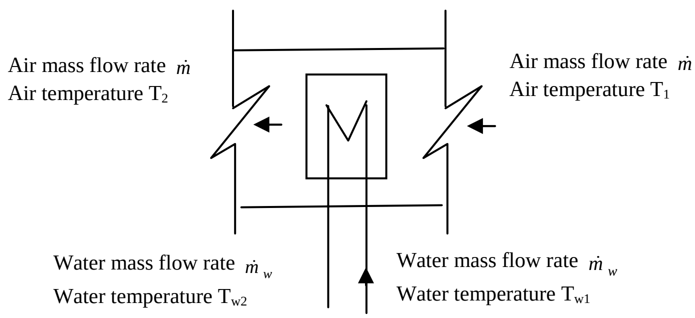
DHW: heat exchanger with gas-fired boiler with economizer.

The alternative No.1 is the base case which is commonly used in Montreal area, and the alternatives No.2 to No.17 are generated with one or more improvements over the base case.

EXERGY ANALYSIS FOR HVAC SYSTEM

In the analysis of the HVAC system, the system is considered to be a combination of blocks that can interact with other blocks and their surroundings through the heat, work, and mass transfer. A block represents a component of the system. The boundary of a block is dependable on the analysis. Figure 1 shows an example of a block, used for the analysis of a hot water air heater, with its inputs and outputs.

The first step in the application of exergy analysis to a HVAC system is the representation of the system by a series of blocks. Inputs and outputs of each block represent the main process parameters. Once a block diagram is generated with the system boundaries defined, it is possible to assess the mass, energy, entropy and exergy balances based on first principle and correlation–based models from product data. The models for all the blocks are then assembled together in order to represent the whole HVAC system. Then the HVAC system can be simulated to derive the different performance parameters: energy and exergy efficiency, energy and exergy demand, entropy generation, exergy destruction. Exergy analysis is conducted under both peak design conditions and annual operating conditions. The results of exergy analysis can locate the inefficient areas of the system where it is necessary to apply some measures to reduce exergy consumption. Further, some exergy related parameters, such as annual energy efficiency, annual exergy efficiency and annual entropy generation can be used as indicators to evaluate and optimize the performance of the system.



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SIMULATION RESULTS AND DISCUSSION

System design conditions and assumptions:

- Indoor design dry-bulb temperature for heating is 21°C [14];
- Outdoor design dry-bulb temperature for heating in winter is -23°C [14];
- Typical meteorological year weather data file for Montreal [9] is used;
- Radiant floor: mean water temperature T_{aw}=30°C, and floor surface temperature T_{fl}=25°C [14];
- Ground source heat pump (GSHP): ground temperature in Montreal area T_{ground}=8°C;
- Domestic hot water (DHW): domestic hot water recovery rate is assumed 0.0105kg/s, supply temperature T_{DHW}=60 °C [14] and the input water temperature 8°C;
- Gas-fired boiler: overall efficiency of boiler (gross energy output divided by energy input) η_{boiler}=75%;
- Air-to-air heat exchanger: sensible heat recovery rate η_{ex}=60%.
- Boiler economizer: heat recovery efficiency of the economizer η_{econ}=45% and fume temperature T_{fume}=210°C.

Results and discussion

The integrated EEE analysis was developed using Engineering Equation Solver (EES) program [15], and then was used for both peak design conditions and annual operating conditions.

First the analysis was conducted for design alternative No.1 (base case). The results show that, at peak design conditions, power generation and transmission accounts for 37% of the total exergy destruction of 26.14 kW, space heating accounts for 36%, ventilation for 20%, and DHW heating for 7%. Therefore, for this case, emphasis should be on decreasing the exergy destruction in the four sectors, in the above sequence. For the power generation and transmission sector, proper selection of the on-site energy sources, such as geothermal energy and natural gas instead of electricity, could decrease the exergy destruction, while for the other three sectors, energy efficient technologies appear more important.

Simulations are then conducted for the design alternatives No.2 to No.17. Table 1 and Table 2 present the simulation results under peak design conditions and annual operating conditions respectively. Alternative No.5 has the best energy performance among all these alternatives: $\eta_1 = 90.2\%$at peak design conditions and $\eta_1 = 90.1\%$ at annual operating conditions. The peak demand is 20.20 kW and annual energy use is 33,689 kWh. However, exergy and entropy analysis tells a different story. Alternative No.10 has the highest exergy efficiency, lowest exergy demand and entropy generation under both peak design and annual operating conditions. Comparison between alternative No.5 and alternative No.10 shows that, at the peak design conditions, the energy efficiency of alternative No.5 is higher than No.10 by 1.7%, but the exergy efficiency of alternative No.5 is lower than No.10 by 7.9%. At the annual operating conditions, the energy efficiency of No.5 exceeds No.10 by 6.2%, but the exergy efficiency of alternative No.5 is 2.5% less than alternative No.10 (Table 3). The reason should be that alternative No.10 integrates the use of geothermal energy, which has relatively small amount of exergy. In addition, it is also noted that the difference of exergy efficiency between the two alternatives at annual operating conditions (2.5%) is much lower than that at peak design conditions (7.9%). This is due to the part load operation of ground source heat pump at most time, which affects the exergy efficiency of alternative No.10.

Table 3 Comparison between alternatives No.5 and No. 10

Alternative No.	Conditions	η_1 %	η_2 %
No.5	Peak design conditions	90.2	15.3
	Annual operating conditions	90.1	8.4
No.10	Peak design conditions	88.5	23.2
	Annual operating conditions	83.9	10.9

Figure 2 shows the configuration of the design alternative No.10. It integrates radiant heating floor, ground source heat pump, air-to-air heat exchanger, hot water air heater, earth tube heat exchanger, and gas-fired water heater. However, it is still not the perfect solution for this specific house, because its exergy efficiency is only 23.2% at peak design conditions, and 10.9% at annual operating conditions. There is still potential to improve its exergy performance. Figure 3 presents the exergy destruction in each component of the design alternative No. 10 under winter design conditions. Power generation and transmission accounts for 32.6% of the total exergy destruction. The exergy destruction is unavoidable when electricity is generated far from the residential areas and transmitted to the end users. However, it can be reduced by using the on-site generation of electricity using renewable sources such as solar energy (e.g., by using photovoltaic panels) or wind (e.g., by using wind mills). Ground source heat pump and gas boiler account for 46.9%, while fans and pumps account for 11.9% of the total exergy destruction. Selection of high efficient ground source heat pump, gas boiler, fans and pumps is a feasible way to increase the exergy performance in this area. The rest 8.6% exergy destruction occurs in radiant heating floor, air-to-air heat exchanger, hot water air heater, earth tube heat exchanger, underground heat exchanger, DHW tank, and exhaust air.

CONCLUSIONS

A number of representative design alternatives of the HVAC system for a house located in Montreal have been analyzed based on integrated EEE analysis. The results of the present path of analysis show the following:

1. Exergy analysis of HVAC system can locate the inefficient areas and point out the areas with great potential for improvement.
2. Integrated with energy analysis and entropy analysis, exergy analysis can be used to evaluate and optimize the performance of HVAC system.
3. The integration of air-to-air heat exchanger, earth tube heat exchanger, radiant heating floor, and ground source heat pump is recommended. Ground source heat pumps are an excellent way to make use of the low quality geothermal energy to match the low quality energy demand of space heating.

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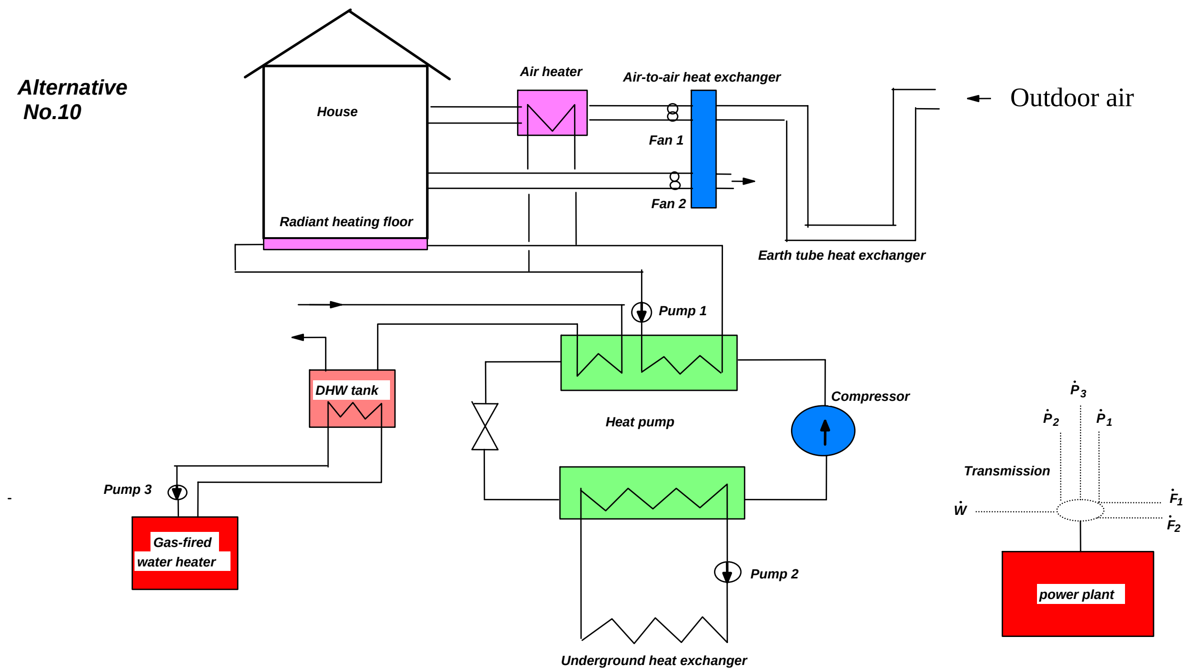

Figure 2 Configuration of the design alternative No.10

Note: $\dot{P}_1$, $\dot{P}_2$, and $\dot{P}_3$ are electricity power inputs for pump 1, pump 2 and pump3;

$\dot{F}_1$ and $\dot{F}_2$ are electricity power inputs for fan 1 and fan 2;

$\dot{W}$ is the electricity power input for compressor of GSHP.

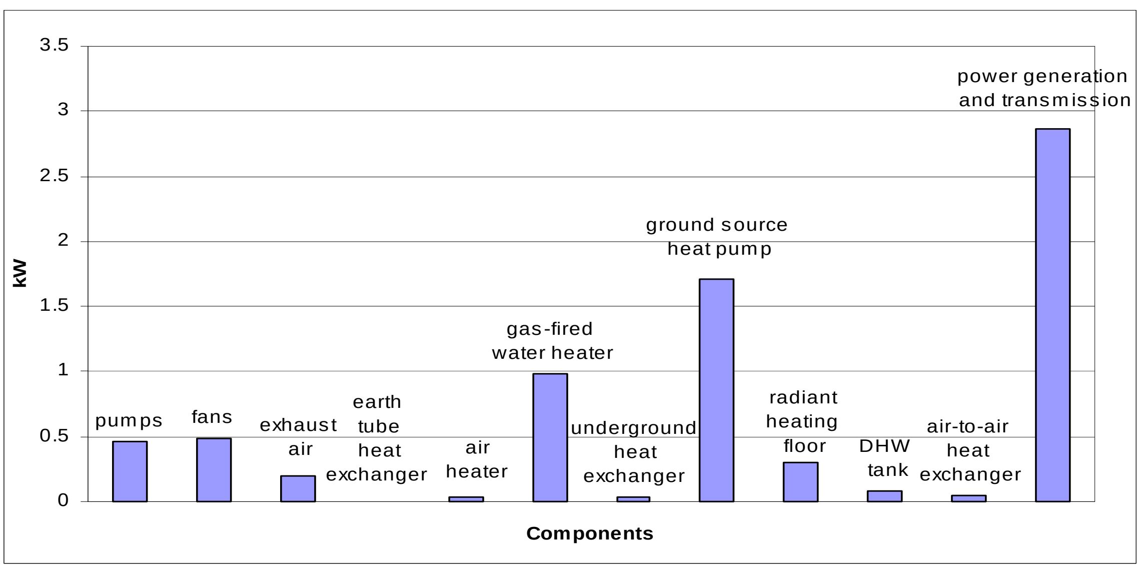

Figure 3 Exergy destruction for design alternative No. 10 at peak design condition (Total exergy destruction is 7.60 KW)

Table 1 Results of integrated EEE analysis at peak design conditions

Alt.	η_1 %	η_2 %	$\dot{S}_{gen,total}$ kW/K	$\dot{Q}_{useful}$ kW	$\dot{Q}_{supplied}$ kW	$\dot{X}_{destroyed}$ kW	$\dot{X}_{supplied}$ kW
1	64.2	7.4	0.10450	18.22	28.37	26.14	28.22
2	76.0	8.7	0.08702	18.22	23.97	21.77	23.85
3	73.1	9.9	0.08168	18.22	24.91	20.43	22.68
4	81.2	12.4	0.06350	18.22	22.43	15.88	18.13
5	90.2	15.3	0.05467	18.22	20.20	13.68	16.15
6	78.1	11.8	0.06717	18.22	23.35	16.80	19.05
7	86.2	14.5	0.05834	18.22	21.12	14.59	17.07
8	70.5	9.5	0.08535	18.22	25.83	21.35	23.59
9	88.6	22.4	0.03116	18.22	20.57	7.80	10.04
10	88.5	23.2	0.03038	18.22	20.58	7.60	9.89
11	77.6	13.3	0.05838	18.22	23.46	14.60	16.85
12	81.5	15.2	0.04971	18.22	22.22	12.44	14.66
13	76.0	13.1	0.06200	18.22	23.98	15.51	17.84
14	79.9	14.8	0.05366	18.22	22.88	13.42	15.76
15	72.7	9.8	0.08228	18.22	25.06	20.58	22.83
16	80.7	12.3	0.06410	18.22	22.58	16.03	18.28
17	89.5	15.2	0.05527	18.22	20.35	13.83	16.30

Table 2 Results of integrated EEE analysis at annual operating conditions

Alt.	η_1 %	η_2 %	$Q_{supplied}$ kWh	Q_{useful} kWh	$X_{supplied}$ kWh	$S_{generated}$ kWh/K	$X_{destroyed}$ kWh
1	61.6	4.1	49260	30343	48989	174.7	46974
2	76.7	5.1	39535	30343	39317	138.6	37302
3	74.2	5.7	40908	30343	37415	130.9	35272
4	80.3	7.0	37796	30343	30762	106.1	28622
5	90.1	8.4	33689	30343	27161	92.3	24873
6	80.3	7.0	37779	30343	30790	106.3	28645
7	89.2	8.3	34027	30343	27497	93.5	25210
8	73.6	5.6	41246	30343	37751	132.2	35608
9	83.7	10.0	36244	30343	21631	72.0	22165
10	83.9	10.9	36153	30343	20788	68.5	19459
11	79.4	7.7	38236	30343	27968	95.6	25807
12	81.2	8.5	37107	30343	25318	85.8	23158
13	80.7	9.0	37587	30343	25847	87.3	23519
14	83.2	10.0	36458	30343	23197	85.7	20869
15	73.0	5.6	41571	30343	38074	133.3	35931
16	79.6	6.9	38103	30343	31111	107.5	28968
17	88.3	8.2	34352	30343	27820	94.7	25532