The exergy approach for the evaluation of heating and cooling technologies; first results comparing steady state and dynamic simulations

A. Angelotti and P. Caputo
Dept. Building Environment Science & Technology,
Politecnico di Milano, Via Bonardi 3, 20133 Milano, Italy

ABSTRACT

Energy saving and emissions reduction are both affected by the energy efficiency of the built environment and the matching between the quality of the energy carrier and the quality of the required energy. To take into account qualitative aspects of energy leads to the introduction of the exergy concept. Heating and cooling of buildings require low valued energy, especially if low temperature heating systems and high temperature cooling systems are used. Nevertheless space conditioning is usually provided through high exergy sources.
This study is related to the IEA ECBCS Annex 49 "Low Exergy Systems for High Performance Buildings and Communities", in the framework of which a research for comparing different technologies for heating and cooling, from both the energy and the exergy perspective has been started, assuming steady state conditions. After that, dynamic simulations have been carried out in order to evaluate the effects of climatic conditions, systems behaviour and envelope's thermal response on exergy performance.

1. INTRODUCTION

Exergy analysis has been applied for the evaluation of energy systems since the early '70s with the aim of finding the most rational use of energy. After a period during which almost scientific efforts were concentrated on energy analysis and CO_2 emission balances, in the last years, exergy has been rediscovered and evenly applied to new scenarios for energy supply both at building and community levels. In fact, in several cases, exergy analysis has been applied in building sector (Schmidt 2004), HVAC systems (Izquierdo Millan 1996, Bilgen 2002, Chengquin 2002, Asada 2003, Asada 2003, Guadalupe Alpuche 2005, Angelotti and Caputo 2007) and renewable energy sources (Koroneos 2001, Ozgener 2005). The exergy approach is at the basis of the IEA ECBCS Annex 37 *Low Exergy Heating and Cooling of Buildings* and also of the recently started IEA ECBCS Annex 49 *Low Exergy Systems for High Performance Buildings and Communities*, to which this paper is related.

To follow a low exergy approach means trying to match the quality levels of energy supply and demand, in order to minimize the utilization of high-value energy resources and the irreversible dissipation of low-value energy into the environment.

In Europe, the energy consumption related to the building sector is about 40% of the total energy consumption and electricity consumption is constantly increasing also due to the cooling demand in summer, in residential buildings too. A large part of this energy requirement could be saved minimizing wastes of energy and promoting a more rational use of primary energy. Globally, these actions could give very valuable results in term of improving comfort conditions both in summer and in winter, control of fossil energy depletion, more equal energy distribution and usage in the World (basic task for the future, considering the energy trend of the emerging Countries) and reduction of greenhouse gases emissions.

The last regulations in energy saving field, in Europe (EPBD Directive) and then in each member Country, underline the important efforts made in order to reduce the energy demand of the building stock; the low exergy approach implies satisfying the remaining heating and cooling demand using low quality energy, when these demands have already been minimized. Currently, most of the energy consumed by the building sector is used to maintain indoor temperatures in a very strict and small range of temperatures (as usual, from 20°C in winter to 26°C in summer, if no comfort adaptive approach is considered), corresponding to a low demand for exergy in space heating and cooling applications. Yet very often this demand is satisfied by high quality energy sources, such as fossil fuels or electricity. The low exergy approach try to invert this trend, proposing a more customized way of energy and exergy supply, taking into account the different final uses with different exergy requirements.

The research is referred to the Italian context and climatic conditions (Milano in the North and Palermo in the South) and considers only the heating and cooling demand of buildings (no evaluations have been carried out about domestic hot water and electricity for lighting and other appliances). Results of a steady state analysis of the energy and exergy performances of different combinations of energy generation and heating and cooling systems (Angelotti and Caputo, 2007) are taken into account and upgraded by a comparison between steady state calculation and dynamic simulations of two systems for heating and two systems for cooling, among those defined in the previously steady state analysis.

The idea to move to dynamic simulations derived from the consideration that exergy is a parameter that refers to both the state of the reference environment and that of the system under analysis. In the case of building analysis, the outdoor air is considered to be the reference environment. In consequence the exergy flows are directly dependent on the outside air temperature. Therefore the use of design or mean outdoor temperatures, as it is done in steady state calculations, may lead to big uncertainties when it comes to the estimation of the exergy flows.

Further, it has to be stressed that, if an adaptive model were adopted for defining indoor comfort conditions, also the temperature of the system under analysis (inside temperature) would depend on environment temperature (outside temperature).

2. STEADY STATE ANALYSIS

Referring to the Italian context, different energy generation scenarios and available systems for heating and cooling were considered; they are based on fossil and/or renewable sources from the side of generations, and based on the most diffuse technologies, from the side of the systems (Angelotti and Caputo, 2007). For each system, steady state energy and exergy evaluations were carried out, assuming design comfort conditions and climatic data for Milano and Palermo and the size of a typical residential unit.

For exergy calculations, a locally and seasonally varying reference environment temperature T_0 and desired inside temperature T_U were assumed. Firstly, T_0 was set equal to the design temperature typically used to size HVAC systems (D.P.R. 1052/1977, UNI 10339/2005). Indoor temperatures were set at design conditions according to Italian standards (without considering an adaptive comfort model).

In the following tables, results about a reference system (air source heat pump, used both for heating and cooling), and an alternative system (condensing boiler and direct ground cooling) are represented. In this paper, the coefficient of performance (COP) of the reference system has been uniformed to the performance trend used in the following dynamic analysis (performances provided in the type 665 of the TESS library of TRNSYS 16.00.0038 were adopted, see also Fig. 1 and Fig. 2), while the energy efficiencies of the alterative systems take into account data from technical literature. It is important to underline that differences between summer conditions in the two locations cannot be appreciated with steady state simulations carried out under these conditions (Table 1 and Table 2), but could be put in evidence with dynamic simulations (Table 5 and Table 6). In this case, dynamic cooling demand should be different in the two cases, as we can suppose considering that climatic conditions and day-night temperature range are different in Milano and in Palermo.

Exergy efficiency ε (ratio between the exergy output and the exergy consumed to produce it) is calculated as follows:

$$\varepsilon = \frac{Ex_U}{Ex_C} \qquad (1)$$

$$Ex_U = Q_U * \left(1 - \frac{T_0}{T_U}\right) \qquad (2)$$

$$Ex_C = \frac{Q_U}{COP} \qquad (3)$$

where Q_U is the energy demand.

On the basis of equations (1), (2) and (3), ε could be written as a function of the energy performance of the system and the previously defined temperatures:

$$\varepsilon = COP * \left|\left(1 - \frac{T_0}{T_U}\right)\right| \qquad (4)$$

where the first factor is the energy efficiency of the system (COP for heat pump and ground cooling or η for boiler) and second factor is defined as Carnot factor.

Table 1. Energy and exergy efficiencies for the reference system (air source heat pump); steady state with design temperatures

	Heating		Cooling	
	Milano	Palermo	Milano	Palermo
T_U °C	20	20	26	26
T_0 °C	-5	5	32	32
$T_0 - T_U$ °C	25	15	6	6
Energy effic. (COP)	2.2	2.7	2.6	2.6
Exergy efficiency %	18.4	13.8	5.2	5.2

Table 2. Energy and exergy efficiencies for the alternative system (condensing boiler - coupled with radiant panels - and direct ground cooling); steady state with design temperatures, design temperatures

	Heating		Cooling	
	Milano	Palermo	Milano	Palermo
T_U °C	20	20	26	26
T_0 °C	-5	5	32	32
$T_0 - T_U$ °C	25	15	6	6
Energy effic. (η or COP)	0.93	0.99	10	10
Exergy efficiency %	7.9	5.1	20.1	20.1

Except for direct ground cooling (because of the higher value of COP), exergy efficiencies for cooling technologies are generally much lower than for heating technologies, due to the different quality of the cooling/heating demand expressed by the second factor of equation (4).

Depending on the system, also the COP could be written as a function of the outside temperature T_0, as happens for the reference system (air source heat pump), while a system less dependent on T_0 has been selected as alternative case.

The first exergy efficiency calculation is related to a pure steady state analysis where design temperatures where adopted; in this case, the use of hourly values of T_0 is not previewed. Despite of this, in order to better understand the effect of T_0 on exergy efficiency, another kind of steady state exergy efficiency has been proposed, based on the monthly mean temperature of the coldest and warmest months for heating and cooling conditions (January and July, respectively). This new calculation permits to give values more similar to those calculated by the dynamic approach, because it is based on a more frequent outside temperature for heating and cooling conditions (while design temperatures are very extreme, with a lower frequency, actually). Results of this new calculation are reported in tables 3 and 4. It is possible to observe that, in this case, cooling performance can not be determined ($T_U > T_0$).

Comparing Table 1 and Table 2 with Table 3 and Table 4, a first difference in terms of exergy efficiency could be observed, also in this case, basically due to the different quality of the cooling/heating demand (Carnot factor). In particular, exergy efficiencies calculated by mean monthly temperatures are ever lower than those referred to design conditions. In other words, the effect of the Carnot factor is more important than that of the energy performances, whose values could be red in Fig. 1 and Fig. 2, in correspondence of the temperatures given in Table 1, Table 2, Table 3 and Table 4.

Table 3. Energy and exergy efficiency for the reference system (air source heat pump); steady state with outside min. and max. monthly mean temperature for heating and cooling, respectively

	Heating		Cooling	
	Milano	Palermo	Milano	Palermo
T_U °C	20.0	20.0	26.0	26.0
T_0 °C	1.7	11.1	25.1	25.5
T_0 - T_U °C	18.3	8.9	-0.9	-0.5
Energy effic. (η or COP)	2.5	3.0	-	-
Exergy efficiency %	15.7	9.2	-	-

Table 4. Energy and exergy efficiencies for the alternative system (condensing boiler - coupled with radiant panels - and direct ground cooling); steady state with outside min. and max. monthly mean temperature for heating and cooling, respectively

	Heating		Cooling	
	Milano	Palermo	Milano	Palermo
T_U °C	20.0	20.0	26.0	26.0
T_0 °C	1.7	11.1	25.1	25.5
T_0 - T_U °C	18.3	8.9	-0.9	-0.5
Energy effic. (η or COP)	0.97	1.03	-	-
Exergy efficiency %	6.1	2.9	-	-

Starting from the characteristic curve of the systems (namely the COP - or η - versus the outside temperature), the full load COP (or η) were calculated for every time step. Also in these cases, the same curves of Fig. 1 and Fig. 2 were applied, hour by hour, in the hourly dynamic simulation. As further improvements of the research, more precise COP curves will be integrated in the next future, for taking into account partial load operation of the different systems.

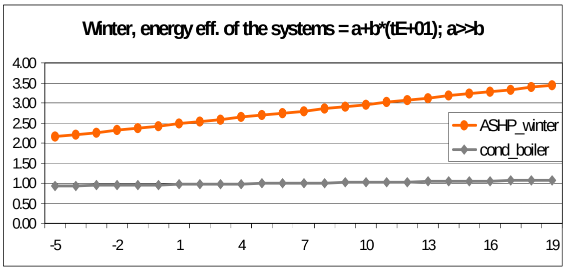

Figure 1. Curves of the energy efficiences, heating systems

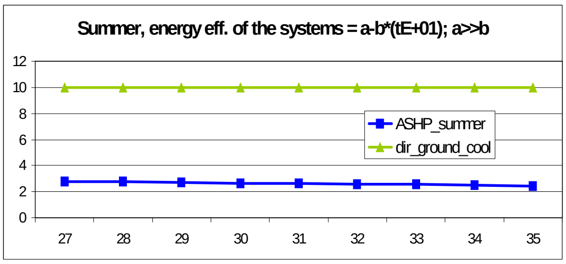

Figure 2. Curves of the energy efficiences, cooling systems

2. DYNAMIC ANALYSIS

In order to improve the exergy efficiency calculation, also the dynamic approach has been considered and a comparison between steady state calculation and dynamic simulation has been carried out.

As first step, the heating and cooling demand of an average Italian residential unit (sample building) has been dynamically simulated using TRNSYS (version 16.00.0038). Also in this case, the first comparison has been carried out for the reference system (air source heat pump) and for the alternative system (condensing boiler and direct ground cooling).

Then, a dynamic exergy analysis taking into account the variation of the exergy demand of the building (equation (2)) and the exergy consumed by the system (equation (3)) has been carried out. In these cases, the hourly external temperatures, referred to the weather TRNSYS file (Meteonorm files available in the weather library of TRNSYS 16.00.0083), have been considered as T_0.

Further, because the sample building adopted includes 3 thermal zones, 3 exergy demands and 3 exergy consumptions (one for each zone) have been calculated for each hour.

As first comparison, monthly values of exergy efficiencies for January and July (corresponding to the extreme months for heating and cooling conditions, respectively) calculated by the dynamic simulations have been compared with those previously obtained with the steady state analysis. Monthly values were preferred to seasonal values because:

- heating seasons are defined by law in Italy, but they are different between Milano and Palermo, due to the different climatic conditions, of course
- cooling seasons are not yet defined by law in Italy
- the excursion of the outside temperature through a season could strongly affect the exergy efficiency calculation and invalidate the comparison.

The exergy efficiencies (ε) reported in Table 5 and Table 6 are calculated as follow:

$$\varepsilon = \left\langle \varepsilon_{zone_i} \right\rangle = \frac{1}{3}\sum_{i=1}^{3} \varepsilon_{zone_i} \qquad (5)$$

where ε_{zone_i} (dynamic exergy efficiencies) may be obtained by averaging the instantaneous exergy efficiencies i.e. as follow:

$$\varepsilon_{zone_i} = \left\langle \varepsilon_{zone_i\,j} \right\rangle = \frac{1}{N}\sum_{j=1}^{N} COP_{ji} * \left(1 - \frac{T_{0_{ij}}}{T_{U_{ij}}}\right) \qquad (6)$$

where j represent the assumed time step (1 hour) and N is equal to 744 hours when one month is considered.

Table 5. Exergy efficiency for the reference system (air source heat pump); dynamic simulation, January and July

	January		July	
	Milano	Palermo	Milano	Palermo
T_U °C	20	20	26	26
$<T_0>$ °C	1.6	12.8	22.3	25.6
$<T_0 - T_U>$ °C	18.4	7.2	-3.7	-0.4
ε %	15.7	9.1	3.6	2.2

Table 6. Exergy efficiencies for the alternative system (condensing boiler - coupled with radiant panels - and direct ground cooling); dynamic simulation, January and July

	January		July	
	Milano	Palermo	Milano	Palermo
T_U °C	20	20	26	26
$<T_0>$ °C	1.6	12.8	22.3	25.6
$<T_0 - T_U>$ °C	18.4	7.2	-3.7	-0.4
ε %	6.2	3.3	11.7	7.7

4. COMPARISON

The parameter chosen for comparing the results obtained by steady state calculations and by dynamic simulations is the exergy efficiency of the building system, according to equation (4), equation (5) an equation (6).

As it can be observed in equation (4), the exergy parameter chosen for the comparison between both simulation methods is not dependent on the energy demand of the building, but only on the quality of the energy and on the energy efficiency of the systems. In consequence, the differences between the dynamic and steady state calculations are only due to differences between the values taken for the outside air temperature, the indoor temperature and energy efficiency of the systems, in the steady state and dynamic analyses.

The comparison is reported in Table 7, where it is possible to appreciate important differences between steady state and dynamic analysis. Generally, steady state analysis with design condition temperatures shows bigger differences than the steady state analysis with monthly mean temperatures, even if is not possible to compare exergy efficiencies in cooling condition for the steady state with monthly mean temperatures (T_0<T_U).

Basically, this result depend on changing reference outside temperature (T_0),

Table 7. Comparison of the exergy efficiencies (values in %)

	January		July	
	Milano	Paler.	Milano	Paler.
Stea_S, design, reference Sys.	18.4	13.8	5.2	5.2
Stea_S, design, alternative Sys.	7.9	5.1	20.1	20.1
Stea_S, month., reference Sys.	15.7	9.2	-	-
Stea_S, month., alternative Sys.	6.1	2.9	-	-
Dynam. month., reference Sys.	15.7	9.1	3.6	2.2
Dynam. month., alternative Sys.	6.2	3.3	11.7	7.7

Table 8 shows the maximum difference between steady state and dynamic, i.e.

difference between steady state with design conditions and dynamic; the first value represents the absolute difference (% values); while the second one represents the ratio between the difference and the steady state exergy efficiency (variation %). Differences are higher for Palermo than for Milano (this means that T_0 is less representative value for temperature trend in Palermo) and for cooling than for heating (because difference between T_0 and T_U is smaller in summer and this affects more the hourly Carnot factor). In general, differences depend on the distance between design T_0 and mean T_0 of the considered period; this means that if the full heating or cooling seasons were considered in the dynamic analysis (instead of the extreme months, i.e. January and July), exergy efficiencies differences of Table 8 would increase.

Table 8. Differences between steady state analysis with design temperature and dynamic analysis

	Stea_St_Des_Temp - Dynamic	Stea_St_Des_Temp - Dynamic
	Reference Sys.	Alternative Sys.
Jan. Milano	Abs. 2.7; rel. 15%	Abs. 1.7; rel. 22%
Jan. Palermo	Abs. 4.7; rel. 34%	Abs. 1.8; rel. 35%
July Milano	Abs. 1.6; rel. 31%	Abs. 8.4; rel. 42%
July Palermo	Abs. 3.0; rel. 58%	Abs. 12.4; rel. 62%

Further, the most energy efficiency change with T_0 (Fig. 3), the bigger the difference between steady state and dynamic are (2.7 vs. 1.7; 4.7 vs. 1.8); while, the behaviour of direct ground cooling is affected by the high value of the COP that increase the weight of the Carnot factor (put equal to 10 and not dependent on outside air temperature).

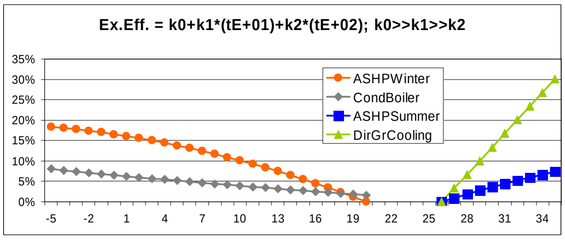

Figure 3. Curves of the exergy efficiences; dependence on T_0 coul be approximated as a second order relation (with system depended coefficients)

In addition, following Fig. 5, Fig. 6 and Fig. 7 show that the variation in the exergy efficiencies is mainly due to the variations of the Carnot factor with outside temperature.

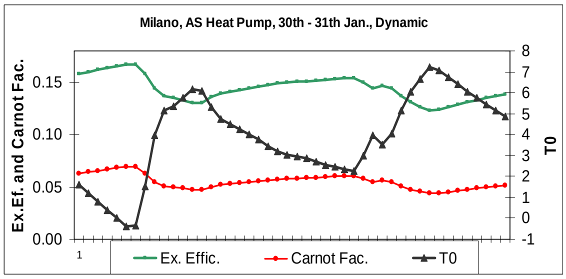

Fig. 4. Example of hourly trend of exergy efficiency (as absolute values) vs. T_0 and Carnot factor (Milano, heating by ASHP)

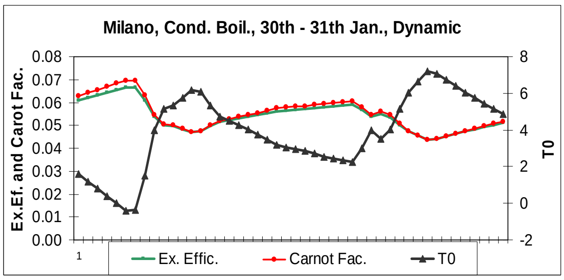

Fig. 5. Example of hourly trend of exergy efficiency (as absolute values) vs. T_0 and Carnot factor (Milano, heating by condensing boiler)

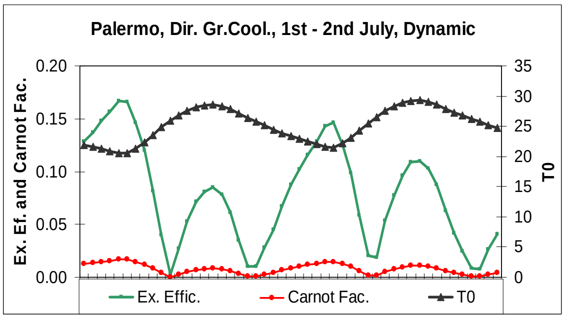

Fig. 6. Example of hourly trend of exergy efficiency (as absolute values) vs. T_0 and Carnot factor (Palermo, direct ground cooling)

5. CONCLUSIONS

Despite of the limitations of the analysis, a first result in terms of comparison between the steady state and dynamic approach in exergy calculation has been stressed.

According to the obtained results, the dynamic approach should be considered in exergy evaluation, in order to take in account correctly the outside temperature. This point seems to be more important in cooling conditions (considering also that in summer, inertia and solar radiation generally play an important role), when the outside temperature is relatively close to the indoor comfort temperature required, and for systems more sensitive to outside temperature. According to this, active cooling should be provided only if very necessary (after applying passive cooling strategies) and, in this case, systems as direct ground cooling and high performance heat pump should be preferred.

The basic role of the Carnot factor, well put in evidence also by the steady state approach, could be analyzed in a more precise way due to the dynamic approach.

Further, dynamic analysis should be carried out by averaging exergy efficiency on the overall season of heating and cooling, instead of on one month. To that end, it is possible to imagine that the larger the seasons, the bigger the differences between steady state and dynamic results. For this reason, it is necessary to define properly also the cooling seasons in different parts of Italy, while heating seasons have been specifically defined yet by law.

Even if dynamic results do not upset steady state results in term of comparison among the different systems (i.e. reference system vs. alternative system), more attention has to be paid at the moment of the design of the envelope/plant system: not only given energy efficiency should be considered, but also the trend of T_0 and the distance between T_0 and T_U during the heating and the cooling season. To that end, a suitable combination of more than one systems could increase the overall energy and exergy efficiency.

As further improvements of the research, more precise COP curves will be integrated in the next future, for taking into account partial load operation of the different systems.

The performed investigation on the sensitivity of the exergy efficiency to the outside temperature allows foreseeing the potential of a dynamic approach, being able to catch the variation of the energy demand and the part load operation of a system. By applying a dynamic analysis, the overall energy chain in detail might be better considered, including also energy storage and distribution, performance of the envelope and so on.

ACKNOWLEDGEMENTS

The work presented in this study is a result of a scientific collaboration in the framework of IEA ECBCS Annex 49 “Low Exergy Systems for High Performance Buildings and Communities”.

Special thanks to Herena Torio from the Fraunhofer Institute for Building Physics (Kassel, Germany), for her precious contribution to this work.

REFERENCES

Angelotti and Caputo. 2007. Energy and Exergy Analysis of Heating and Cooling Systems in the Italian Context. *Proceedings of the CLIMAMED Conference*. Genova, Italy.

Annex 37. 2003. *International Energy Agency ECBCS – Low Exergy Heating and Cooling of Buildings* – Annex 37, Web Homepage, http://www.lowex.net/

Annex 49. 2006. *International Energy Agency ECBCS – Low Exergy Systems for High Performance Buildings and Communities* – Annex 49, Web Homepage, http://www.annex49.org/

Asada H., Boelman E.C. 2003. Exergy analysis of a low temperature radiant heating system. *Proceedings of the Eighth International IBPSA Conference*, pp. 71-78, Eindhoven, Netherlands.

Bilgen E., Takahashi H. 2002. Exergy analysis and experimental study of heat pump systems. *Exergy*, Vol. 2, pp. 259-265.

Chengqqin R., Nianping L. Guangfa T. 2002. Principles of exergy analysis in HVAC and evaluation of evaporative cooling schemes. *Building and Environment*, Vol. 37, pp. 1045-1055.

Danny Harvey L.D. 2006. *A Handbook on Low-Energy Buildings and District-Heating Systems*, Earthscan, UK.

D.P.R. 1052, 28-6-1977.

Guadalupe Alpuche M., Heard C., Best R., Rojas J. 2005. Exergy analysis of air cooling systems in buildings in hot humid climates. *Applied Thermal Engineering*, Vol. 25, pp. 507-517.

Hennings H.M. 2004. *Solar-Assisted Air-Conditioning in Buildings*, SpringerWien, NewYork.

Izquierdo Millan M., Hernandez F., Martin E. 1996. Available solar exergy in an absorption cooling process. *Solar Energy*, Vol. 56, No. 6, pp. 505-511.

Kilkis B. 2005. "*A road map for emerging low-exergy HVAC systems*". International Journal Exergy, Inderscience publishers, Vol. 2 No. 4, 2005.

Koroneos C., Spachos T., Moussiopoulos N. 2001. *Exergy analysis of renewable energy source.* Elsevier.

Moran M.J. and Shapiro H.N. 1998. *Fundamentals of Engineering Thermodynamics.*3rd Edition, John Wiley & Sons, New York, USA.

Ozgener L., Hepbasli H., Dincer I. 2005. Energy and exergy analysis of geothermal district heating systems: an application. *Building and Environment*, Vol. 40, pp. 1309-1322.

Schmidt D. 2004. Design of Low Exergy Buildings-Method and a Pre-Design Tool. *The International Journal of Low Energy and Sustainable Buildings*, Vol. 3, pp. 1-47.