Available online at www.sciencedirect.com
SCIENCE DIRECT®

Energy and Buildings 37 (2005) 529–544

ENERGY and BUILDINGS

www.elsevier.com/locate/enbuild

Modeling energy efficiency of bioclimatic buildings

A.F. Tzikopoulos, M.C. Karatza, J.A. Paravantis*

Department of Technology Education and Digital Systems, University of Piraeus, 80 Karaoli and Dimitriou Street, Piraeus 185 34, Greece

Received 20 July 2004; received in revised form 10 September 2004; accepted 23 September 2004

Abstract

The application of bioclimatic principles is a critical factor in reducing energy consumption and CO_2 emissions of the building sector. This paper develops a regression model of energy efficiency as a function of environmental conditions, building characteristics and passive solar technologies. A sample of 77 bioclimatic buildings (including 45 houses) was collected, covering Greece, other Mediterranean areas and the rest of Europe. Average energy efficiency varied from 19.6 to 100% with an average of about 68%. Environmental conditions included latitude, altitude, ambient temperature, degree days and sun hours; building characteristics consisted in building area and volume. Passive solar technologies included (among others) solar water heaters, shading, natural ventilation, greenhouses and thermal storage walls. Degree days and a dummy variable indicating location in the Mediterranean area were the strongest predictors of energy efficiency while taller and leaner buildings tended to be more energy efficient. Surprisingly, many passive technologies did not appear to make a difference on energy efficiency while thermal storage walls in fact seemed to decrease energy efficiency. The model developed may be of use to architects, engineers and policy makers. Suggestions for further research include obtaining more building information, investigating the effect of passive solar technologies and gathering information on the usage of building.

Keywords: Bioclimatic architecture; Sustainable architecture; Energy efficiency; Passive solar technologies; Regression model

1. Introduction

The term bioclimatic (or sustainable) architecture refers to an alternative way of constructing buildings so that local climatic conditions are taken into account and a number of passive solar technologies are utilized in order to improve energy efficiency; the term passive solar technologies refers to heating or cooling techniques that passively absorb (or protect from, e.g. natural shading) the energy of the sun and have no moving components. Bioclimatic structures are built in such a way that, during winter months, exposure to cold temperatures is minimized and solar gains are maximized; during the summer, bioclimatic structures are shaded from the sun and various cooling techniques are employed [1–3], often with the aid of renewable energy sources [4]. In addition, locally available building materials may be used.

It is estimated that 4.5 out of 6 billion tones of carbon emitted worldwide from human activities may be attributed to industrialized countries [5]. Approximately half of this is due to buildings (in one form or another). Building more energy efficient houses may reduce carbon emissions by 60% or more, which translates to 1.35 billion tones of carbon, an amount equal to the savings proposed by the environment conferences in Rio and Berlin; as a side benefit, building more bioclimatic homes will conserve conventional energy sources and possibly reduce dependence on oil imports. Because of this potential for significant savings in energy consumption and reduction in greenhouse gas emissions, bioclimatic architecture has received a fair amount of attention all over the world in the last few years (e.g. [6–9]) and is regarded as an important parameter in contemporary architecture [10]. In Greece, for instance, the Rule for Rational Use and Energy Savings (RRUES) that was enacted in 1998, stipulates that energy consumption reduction measures be made compulsory for all buildings by 2007 [11,12].

Although there exist numerous case studies that examine isolated bioclimatic projects or buildings (such as [13–16] as well as model codes that predict energy consumption of a

* Corresponding author. Tel.: +30 210 4142771; fax: +30 210 4142753.
E-mail address: jparav@unipi.gr (J.A. Paravantis).

0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2004.09.002

single building (see [17] for a brief but complete review) based on either energy parameters or physical laws or performance data, little effort has been invested in analyzing a larger sample of bioclimatic structures using statistical techniques. This paper attempts to build a regression model in order to understand how energy efficiency of bioclimatic buildings depends on environmental (including climatic) conditions, building characteristics and passive solar technologies that are commonly utilized.

2. Background

Orientation of buildings so that they could utilize solar input more efficiently, first took place in Greece 2500 years ago [18]. A few centuries later, Rome bathhouses were built so that their windows faced the south to let in the warmth of the sun [19]. In 1200 A.D., the Anasazi (regarded as ancestors of Pueblo Indians in North America) built cliff dwellings that captured the winter sun [20]. More recently, in 1891, Clarence Kemp, a Baltimore inventor, patented the first commercial solar water heater [21]. In 1940, the Sloan Solar House in Chicago, designed by Keck, became the first contemporary building making use of passive solar heating [18]. In 1953, Dan Trivich of Wayne State University, made the first theoretical calculations of the efficiencies of various materials based on the spectrum of the sun [20]. In 1977, the U.S. Department of Energy launched the National Renewable Energy Laboratory of the Solar Energy Research Institute, a federal facility dedicated to harnessing power from the sun [22]. Finaly, in 1994, the National Renewable Energy Laboratory (formerly known as the Solar Energy Research Institute) completed a construction of its Solar Energy Research Facility, which was recognized as the most energy-efficient of all U.S. Government buildings worldwide [23].

Energy consumed in the building sector constitutes a significant proportion of total energy consumption. Sources place the amount of energy expended in the building sector in Europe to about 40–45% of total energy consumption [24]; about two thirds of this amount is used in private buildings. Other sources claim, that in industrialized countries, energy usage in buildings is responsible for approximately 50% of carbon dioxide emissions [25–27]. Solar energy, for example, covers 13% of primary energy used in buildings; this percentage could increase to 50% by 2010 while in some cases it could even reach 57% [28].

In Greece, the use of energy in buildings such as public and private buildings, schools, hospitals, hotels and athletic facilities, constitutes 30% of total national energy demand and contributes about 40% of carbon dioxide emissions [29]. Heating and refrigeration of buildings consume the largest part of energy expended in domestic uses [30]. Taking into consideration that only about 3% of buildings in Greece have been constructed after 1981 (when heat insulation regulations were put into effect), it may be concluded that the limited application of insulation in the majority of residences causes significant energy losses in Greece [31].

A bioclimatic building may be so economically efficient that it consumes even 10 times less energy for heating compared to a conventional European building [32]. The additional cost of a typical bioclimatic structure is usually around 3–5% and in most cases less than 10% [33]; this cost is usually returned within a few years [34]. Bioclimatic technologies (such as passive solar systems) may also be retrofitted to existing structures although, in such cases, the cost is typically a little higher. In addition to conservation of energy, bioclimatic architecture may improve day lighting and indoor comfort conditions. For instance, in a natural ventilation design project for houses in Thailand, it was found that, although total energy saving in the winter months was less than 20%, indoor air quality was significantly improved and this was an important feature justifying the design [35].

The total amount of energy used for a building includes [36]:

- Production energy (also known as embedded energy), which is the energy expended during production, assembly, maintenance, alteration, demolition and recycling of building materials.
- Induced energy, which is the energy consumed for construction; architects, civil engineers and construction crews control the consumption of energy during the construction phase.
- Operation energy, which is the energy necessary to maintain required levels of comfort; obviously, energy consumed for the operation of a building represents a more or less steady amount for a longer period of time.
- Grey energy, which refers to conversion losses incurred during transport of materials, construction of building, heating etc.

Two important observations may be made. On one hand, energy required for a building is not only the amount used during its operation; production energy, induced energy and grey energy are also needed and they increase consumption of non-renewable energy resources as well as carbon emissions. On the other hand, operation energy (which, along with the part of grey energy that concerns operation, is the only group that keeps increasing during the lifetime of a structure) may be significantly reduced if bioclimatic principles are applied during design and construction.

Energy efficiency of a building based on bioclimatic principles is determined by a set of environmental, technical and usage factors. First of all, the location of a building is a major determinant; geographic latitude that is related to mean temperature (with lower temperatures in places of greater latitude) should be a major influence. Also, location of a building in an area with continental climate increases dryness and thermal variation while location in the Mediterranean implies mild winters and relatively cool summers (i.e. lack of temperature extremes). Additional factors include altitude (absolute height above sea level) that is associated with a fall in average temperature, an increase in temperature variation and a fall in humidity; topographic relief that is related to microclimatic variations especially in relation to the sun and prevailing winds; and vegetation that promotes thermal stability and increases humidity [37].

Bioclimatic architecture literature recognizes the following factors to be taken into account in building construction [38]:

- topography, e.g. slope, site orientation, site views;
- movement of the sun and its impact during the year (i.e. solar altitude and azimuth);
- climatic conditions including prevailing wind patterns, incoming solar radiation, temperature, air moisture;
- environmental conditions such as daylight and shading of the construction site; daylight may reduce consumption of artificial lighting from 40 to 80% [39];
- mass, volume and size of building;
- local architectural standards;
- availability of local building materials.

Several studies have rendered significant results concerning the conservation of energy that may result from the use of passive systems. Savings that average 50% in space-heating energy use (compared to conventional practices that are set by building regulations) have already been demonstrated by projects built and operated in the UK: the best of these examples achieve impressive savings in the order of 60–75% [5]. Nevertheless, the wide variety in technologies found in bioclimatic structures indicates that no general rules apply in bioclimatic architecture. Different locations in different countries are characterized by unique sets of conditions and these decide the exact systems to be implemented. Oke, [40] as quoted by Ratti et al. [41], states that there are ‘‘almost infinite combinations of different climatic contexts, urban geometries, climate variables and design objectives . . . obviously there is no single solution, i.e. no universally optimum geometry’’ although there exist predominant urban types associated with certain climate types, such as the courtyard type associated with hot and arid climate. It is precisely the role of environmental condition, building features and passive solar technologies on an aggregate level that this work attempts to quantify.

3. Methodology

The goal of this work is to develop a regression model linking energy efficiency to a number of independent variables including geographical location, climatic conditions (that determine heating and cooling requirements), buildings characteristics (including area and volume) and a number of alternative passive technologies used in bioclimatic architecture (such as shading, thermal storage walls and greenhouses).

A sample of European bioclimatic buildings is assembled; data collection is carried out using questionnaire-based interviews (for buildings in Greece), project reports, monographs, textbooks, journal papers and various online sources (for buildings in the rest of Europe). Our work is carried out in the following phases:

1. Data description: In this phase, we graph and tabulate building types, buildings per country and area (e.g. Mediterranean versus rest of Europe), passive technologies, energy performance per building type etc.
2. Model formulation: In this phase, based on our a priori expectations, we hypothesize a linear functional form for the model and investigate the relationship of independent variables to energy efficiency (via scatter plots, correlation coefficients and auxiliary regressions) in order to develop alternative model specifications.
3. Model estimation: Finally, we estimate and compare these alternative model specifications in order to select the best model. Then we discuss implications born by our model on the state of the art.

Minitab version 14.12 was used for graphing and Minitab with SYSTAT version 10.2 were used for statistical analysis.

4. Data description

Data were collected for 77 buildings as shown in Table 1.

Table 1
Sample variables

Variable	Name	Measurement
Energy efficiency	EFFICIENCY	%
Latitude	LATITUDE	°
Altitude	ALTITUDE	m
Ambient temperature (January)	AMBTEMPJAN	°C
Ambient temperature (July)	AMBTEMPJUL	°C
Degree days	DEGRMONTHS	Months
Sun hours	SUNDAYS	Days
Building area	M2	1000 m^2
Building volume	M3	1000 m^3
Height proxy	HEIGHTPROXY	m
Greenhouse	GREENHOUSE	Dummy
Shading	SHADING	Dummy
Thermal storage wall	THSTORWALL	Dummy
Natural ventilation or aeration	NATURAIR	Dummy
Direct profit	DIRPROFIT	Dummy
Solar water heater	SOLWATHEAT	Dummy
Air tower	AIRTOWER	Dummy
Blanco wall system	BWALLSYS	Dummy
Container of water	CONTWATER	Dummy
Convective loop	CONVLOOP	Dummy
Evaporation unit	EVAPUNIT	Dummy
Ice banks	ICEBANK	Dummy
Rock bed	ROCKBED	Dummy

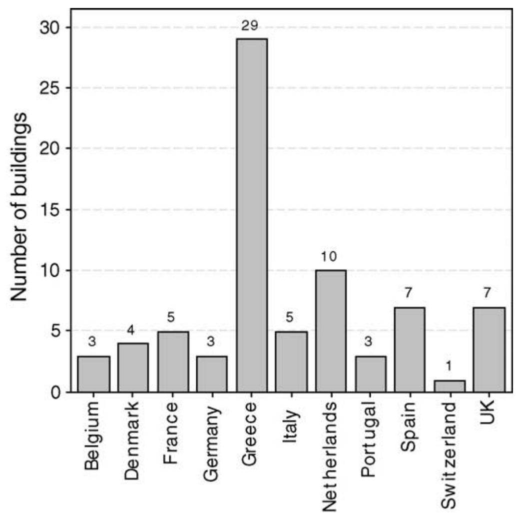

Fig. 1. Buildings per country.

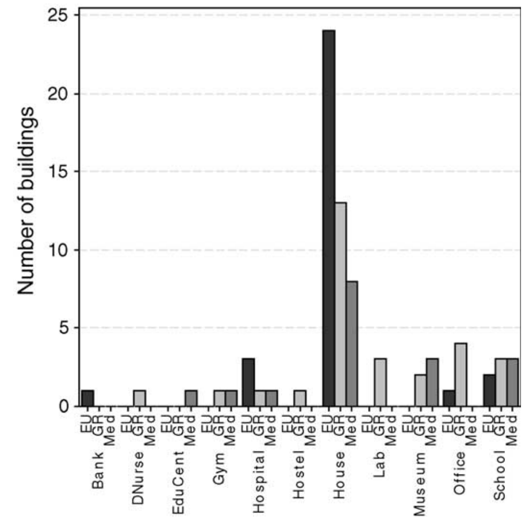

Fig. 3. Buildings per type and area.

Energy efficiency is equal to the percentage of saved by a energy building built on bioclimatic principles. Also, we express degree days and sun hours into degree months and sun days, respectively in order to improve scaling of data; building area and volume are expressed in thousand m^2 and m^3, respectively for the same reason. Finally, we calculate a new variable, named height proxy, as volume over area of building; taller and leaner structures will tend to have higher values while stubby structures will tend to have low values of the height proxy variable.

The number of buildings per country and building type is shown in Figs. 1 and 2. Greece (29 buildings or 38% of the total) and Netherlands (10 or 13%) were represented with the largest number of data points in the sample; all other countries were represented with less than 8 buildings each. As shown in Fig. 2, most buildings (45 or 58.4%) were homes while 8 (10.4%) were schools (one was characterized as educational center).

A breakdown of buildings to those in the Mediterranean (including Greece, Italy, Spain, the South France and Portugal which, although it does not border the Mediterranean, has Mediterranean climate) and all other European countries is shown in Fig. 3. Average energy efficiency was about 68% with a minimum of 19.6% and a maximum of 100%; its distribution is shown in Fig. 4.

Figs. 5 and 6 indicate the spread of efficiency values among countries and building types; black dots indicate the efficiency of individual buildings (per group) while grey bars indicate the average efficiency of each group. Fig. 5 shows that average efficiency varied by country, being highest in Switzerland (represented by a single data point) followed by Spain (7 data points) and Greece (29 data points). Fig. 6 shows how average efficiency varied by building type,

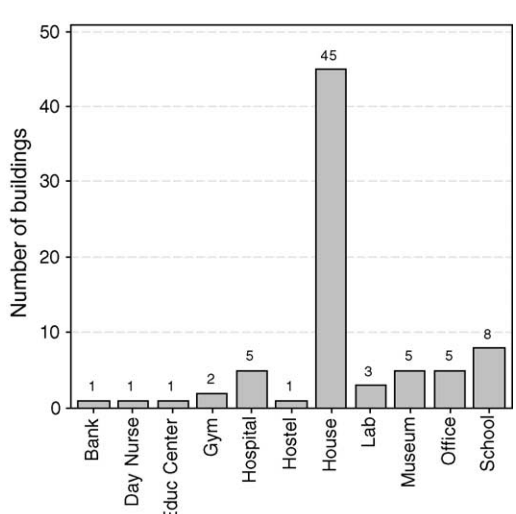

Fig. 2. Buildings per type.

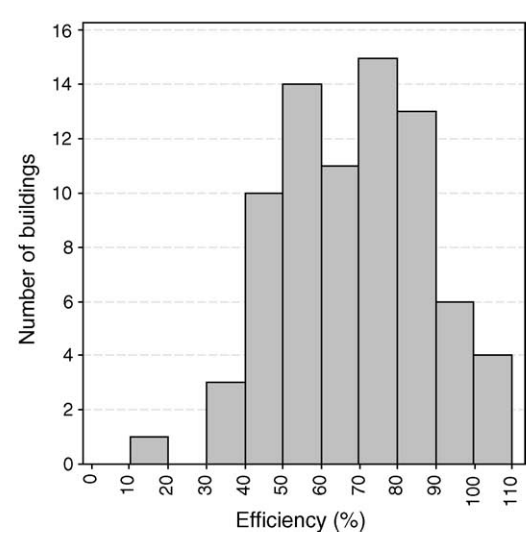

Fig. 4. Distribution of energy efficiency.

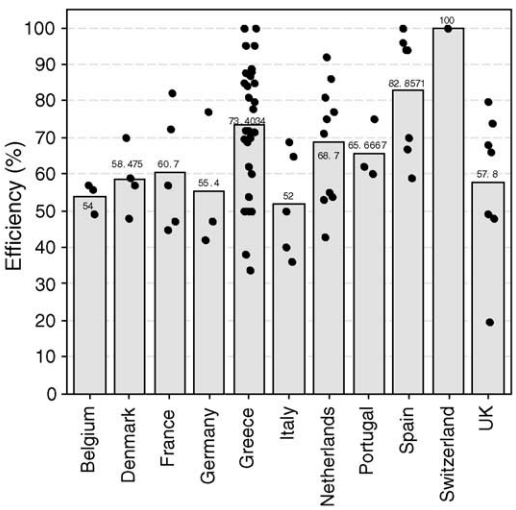

Fig. 5. Average efficiency per country.

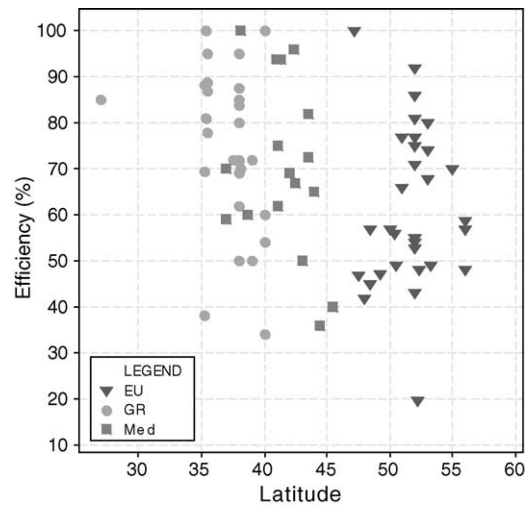

Fig. 7. Energy efficiency vs. latitude by country and area ($R = -0.342$; $p = 0.002$).

appearing to be higher in public use buildings (although these were represented by very few data points: one educational center, two gymnasiums, one day nursery, one hostel and one bank); efficiency in schools (8 data points) was rather low while homes were characterized by the widest range of efficiency values.

Turning now to the relationship of energy efficiency to explanatory variables, Fig. 7 shows that energy efficiency was negatively associated with latitude: as one moves to the north, further away from the equator, energy efficiency falls (Pearson correlation coefficients and associated uncorrected p-values for the hypothesis test of the correlation coefficient being equal to zero are shown in parentheses). Fig. 8 shows a similar plot for altitude; there is a clustering of points in relatively low altitudes (below 200 m) and the correlation is insignificant.

Energy efficiency was positively associated with both January and July ambient temperatures, shown in Figs. 9 and 10. The correlation appears to be a bit stronger in the case of ambient temperature for January although both were statistically significant.

We note that if the unusual isolated data point appearing in the lower left of Fig. 10 was excluded, the correlation coefficient of energy efficiency and July ambient temperature would be equal to 0.239 ($p = 0.066$).

Fig. 11 shows a rather strong positive association between energy efficiency and degree days (expressed in months). Similarly, Fig. 12 shows a moderately strong positive association between efficiency and sun hours (expressed in days); again, if the unusual building in the lower left of the figure were excluded, R would be equal to 0.378 ($p = 0.003$). Overall, degree days render the strongest association with energy efficiency among all locational and environmental variables.

We now turn our attention to building characteristics. Fig. 13 shows a weak negative association between energy

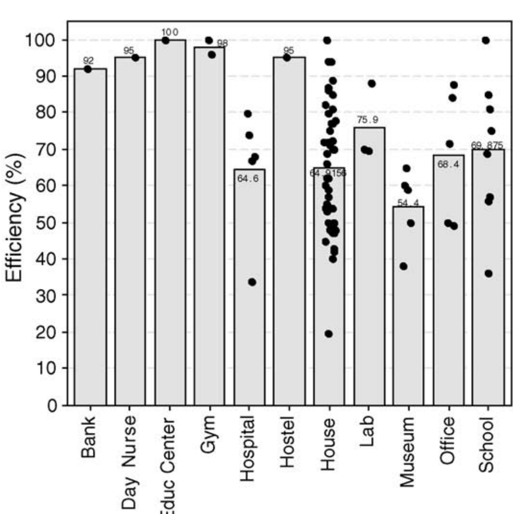

Fig. 6. Average efficiency per building type.

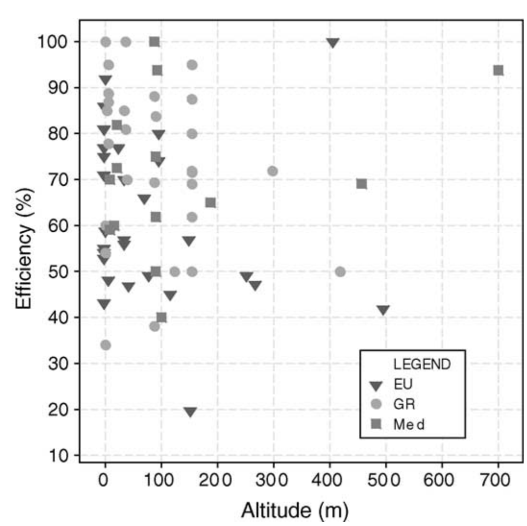

Fig. 8. Energy efficiency vs. altitude ($R = -0.026$; $p = 0.828$).

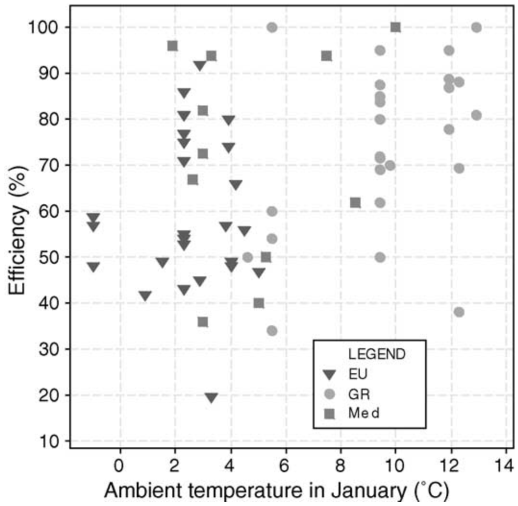

Fig. 9. Energy efficiency vs. January ambient temperature ($R = 0.397$; $p = 0.002$).

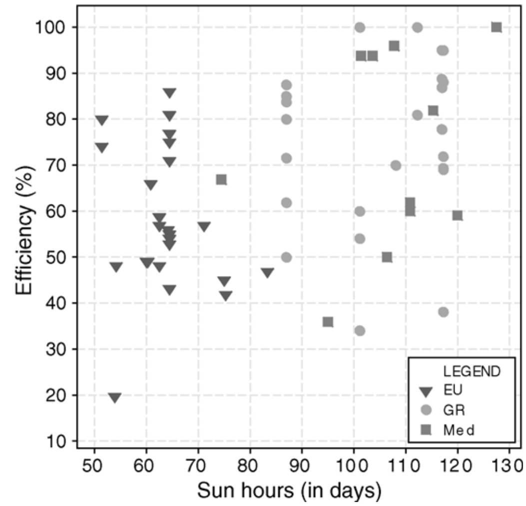

Fig. 12. Energy efficiency vs. sun days ($R = 0.415$; $p = 0.001$).

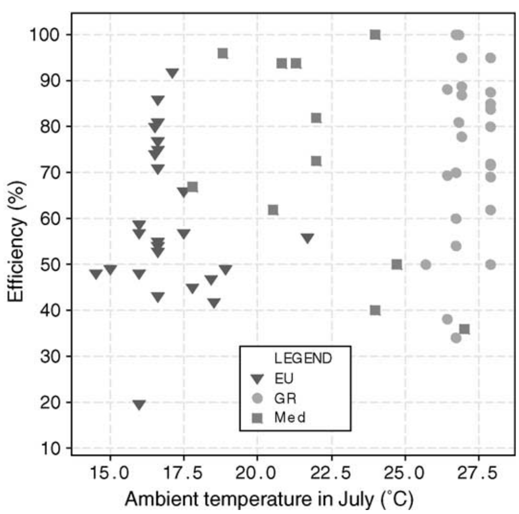

Fig. 10. Energy efficiency vs. July ambient temperature ($R = 0.274$; $p = 0.032$).

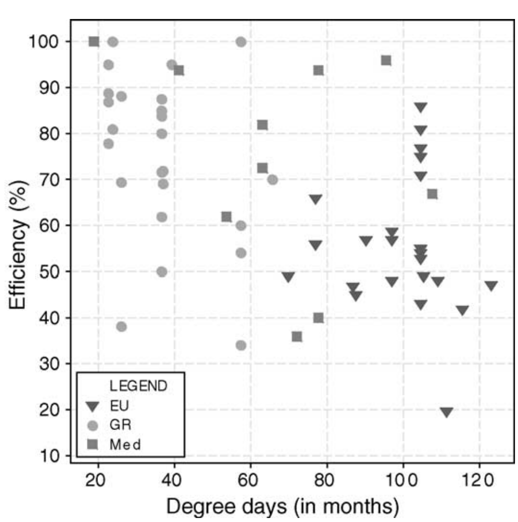

Fig. 11. Energy efficiency vs. degree months ($R = -0.494$; $p = 0.000$).

efficiency and building area (a Greek hospital with an area of 70,000 m^3 was excluded); if this hospital were included in computations, R would be equal to -0.228 ($p = 0.073$) as shown in Table 3. Similarly, Fig. 14 shows a weak positive association of efficiency and building volume. In both of these figures, there is a clustering of points towards smaller values of the x-axis.

Fig. 15 shows that the height proxy variable was positively associated with energy efficiency and the correlation coefficient was larger than in the case of the previous two building characteristics; yet we note that it appears that the variation in energy efficiencies increases with diminishing values of the height proxy.

We now turn out attention to passive solar technology characteristics. Data for binary (dummy) independent variables that represent the presence of absence of specific

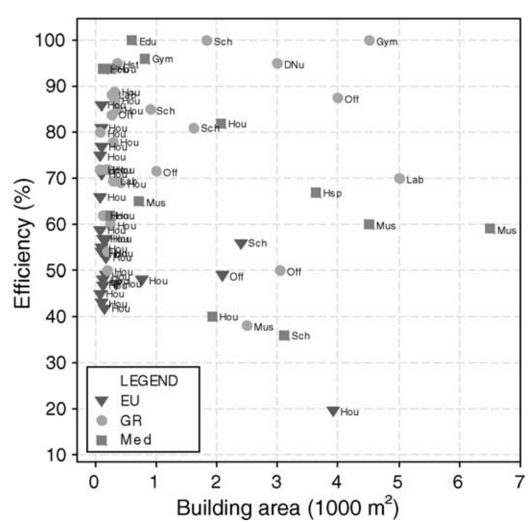

Fig. 13. Energy efficiency vs. building area ($R = -0.070$; $p = 0.587$) (one very large building excluded).

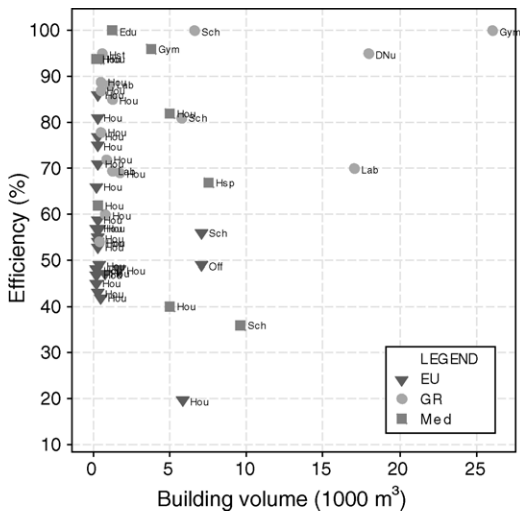

Fig. 14. Energy efficiency vs. building volume ($R = 0.187$; $p = 0.204$).

passive technologies were available in 56 out of 77 observations and are presented in Table 2.

Based on the frequency of occurrence of their values in our sample, only the following may be of use in our investigation:

1. greenhouse,
2. thermal storage wall,
3. shading,
4. natural aeration (possibly),
5. direct profit (possibly),
6. solar water heater (possibly).

Average energy efficiency values among presence/absence of passive technologies are shown is Figs. 16–21 (two-sample t-tests with their associated two-tail p-values are indicated in parentheses).

Table 2
Passive technology variables

Variable	Yes	%	No	%
GREENHOUSE	30	53.6	26	46.4
SHADING	32	57.1	24	42.9
THSTORWALL	21	37.5	35	62.5
NATURAIR	49	87.5	7	12.5
DIRPROFIT	51	91.1	5	8.9
SOLWATHEAT	5	8.9	51	91.1
AIRTOWER	1	1.8	55	98.2
BWALLSYS	1	1.8	55	98.2
CONTWATER	1	1.8	55	98.2
CONVLOOP	1	1.8	55	98.2
EVAPUNIT	1	1.8	55	98.2
ICEBANKS	1	1.79	55	98.2
ROCKBED	1	1.79	55	98.2

Surprisingly, the presence of greenhouses, thermal storage walls and natural aeration schemes seems to be associated with slightly lower energy efficiency values; this may well be a spurious effect caused by the distribution of values in our non-random sample, which is difficult to control. On the other hand, shading, direct profit and solar water heater technologies appear to be associated with larger efficiencies, as expected. In all of these cases, as t-test results indicate, none of the differences in efficiencies are statistically significant although, as in the case Figs. 20 and 21 this may be an artifact of unequal distribution of buildings among passive technology groups.

5. Model formulation

Having looked at a priori expectations based on literature findings and having described the distribution and correlation of dependent and independent variables, we now examine statistical measures of interest in formulating our model. Table 3 shows Pearson correlation coefficients

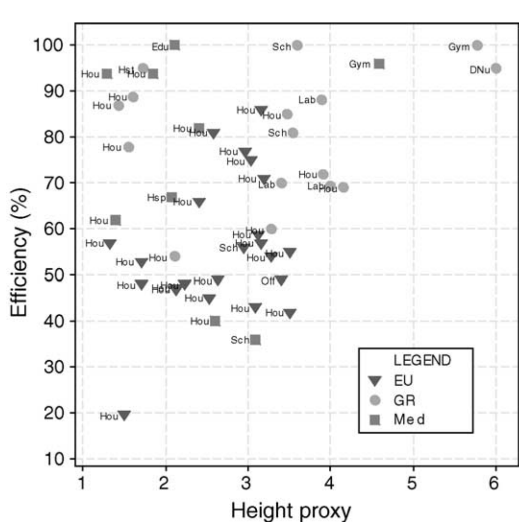

Fig. 15. Energy efficiency vs. height proxy ($R = 0.247$; $p = 0.090$).

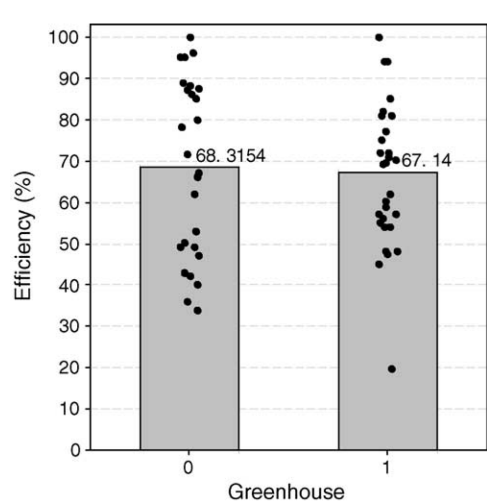

Fig. 16. Average efficiency among greenhouse groups ($t = 0.22$; $p = 0.828$).

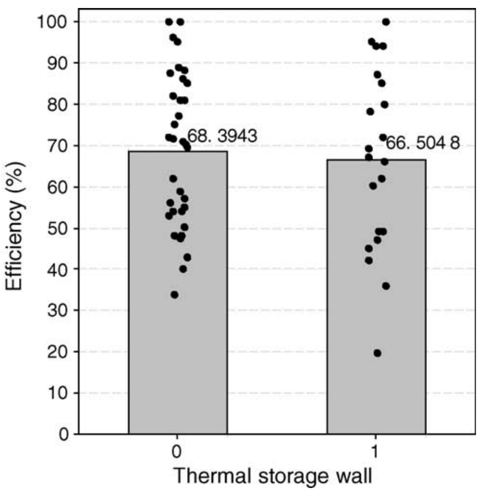

Fig. 17. Average efficiency among thermal storage wall groups ($t = 0.33$; $p = 0.744$).

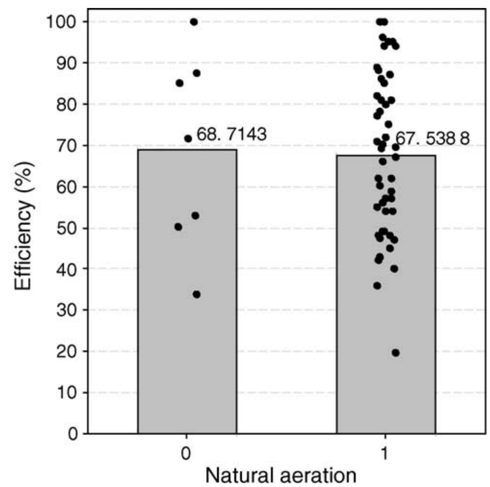

Fig. 19. Average efficiency among natural aeration groups ($t = 0.12$; $p = 0.904$).

between energy efficiency and quantitative independent variables (missing values were deleted pairwise and values in parentheses represent uncorrected probabilities resulting from testing the significance of the coefficients); in the case of building area, two correlation coefficients are computer: one for all the values (M2_1000) and one when the large hospital is excluded (M2_1000 < 70). On one hand, strong correlation between energy efficiency (the dependent variable) and the other variables (independent variables) provide additional support to our prior expectations and provide a supplemental guide as to which independent variables may be included in our model; on the other hand, strong correlations between independent variables, indicate independent variable pairs that are likely to create collinearity problems in a regression model and should thus be avoided or used with caution.

As already shown in Figs. 7–15, the following environmental variables are significantly associated with energy efficiency (correlation sign shown in parentheses):

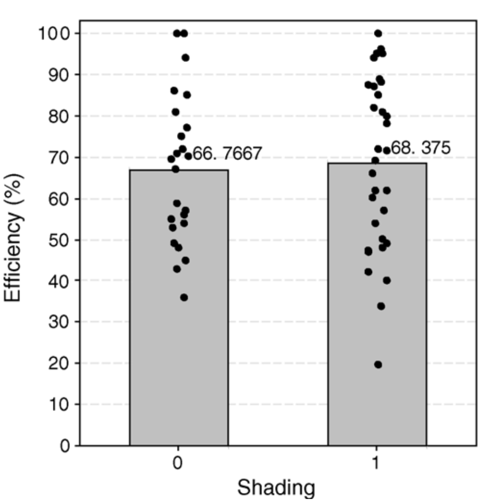

Fig. 18. Average efficiency among shading groups ($t = -0.31$; $p = 0.760$).

- latitude (−),
- ambient temperature of January (+) and ambient temperature of July (+) although the January temperature displays a stronger association,
- degree months (−) is the environmental variable that displays the strongest association with performance,
- sun days (+) is also strongly associated with energy efficiency.

Regarding building characteristics:

- The correlation of building area (−) with energy efficiency is marginally insignificantly (at a 7.3% significance level) but if we exclude a large Greek hospital it becomes very insignificant ($R = -0.070$; $p = 0.587$).
- Volume (+) is not significantly associated with energy efficiency.
- Height proxy is positively (+) but not significantly associated with energy efficiency (91% confidence level)

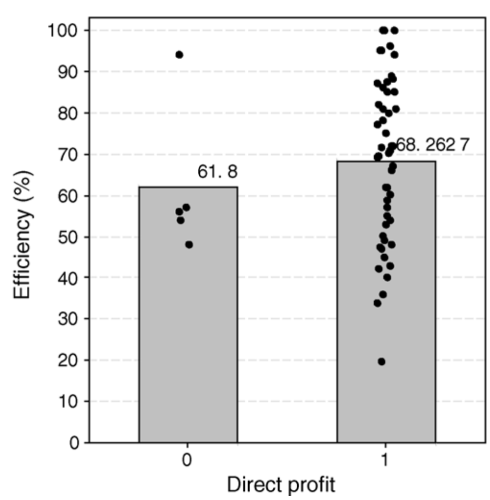

Fig. 20. Average efficiency among direct profit groups ($t = -0.75$; $p = 0.497$).

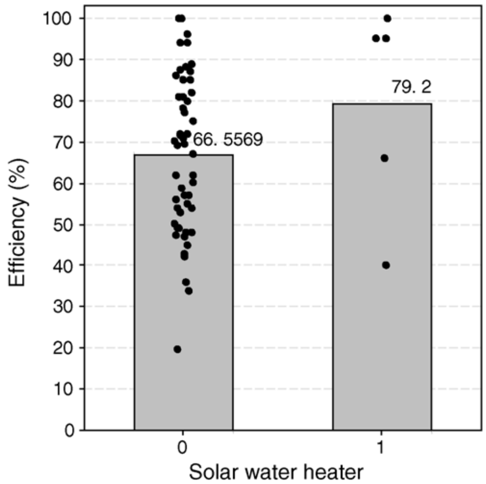

Fig. 21. Average efficiency among solar water heater groups ($t = -1.07$; $p = 0.344$).

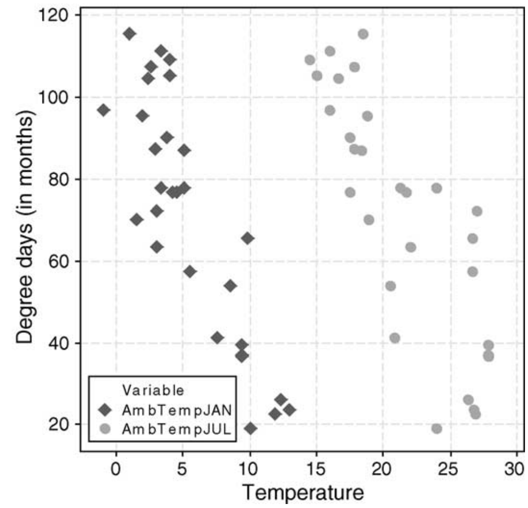

Fig. 22. Degree days vs. January and July temperatures.

although its correlation value is higher than those of area and volume.

The following independent variable pairs appear to be strongly correlated with one another, precluding their simultaneous inclusion in a regression model:

- With the exception of altitude, all environmental variables (latitude, degree days, sun hours and both temperatures) are very strongly ($p = 0.000$) associated with one another, therefore only one could be safely used in a regression model; combinations that could be attempted with caution are (in order of preference):
  - i sun hours with January ambient temperature ($R = 0.751$),
  - ii sun hours with July ambient temperature ($R = 0.794$),
  - iii January and July ambient temperatures ($R = 0.806$),
  - iv degree months with sun days ($R = -0.823$), an appealing combination because degree months is associated with cold weather while sun days is associated with sunny weather.
- Area and volume are strongly associated ($R = 0.893$) and could only be used jointly with great caution.
- The height proxy is significantly associated with building area ($R = 0.309$; $p = 0.003$) but the value of the correlation coefficient is rather low so they could probably be used in the same model.
- The height proxy is more significantly associated with building volume ($R = 0.568$; $p = 0.000$) but, again, the value of the correlation coefficient is relatively low so we could attempt to include them in the same model.

Since individual correlation coefficients only show association between pairs of variables, in order to anticipate multicollinearity effects, we employ auxiliary regressions each independent variable as a function of the rest, shown in Tables 4 and 5.

The following conclusions may be drawn from Table 4:

- Of all the independent variables, latitude is the most highly explained by the temperature variables, sun hours and altitude and will present multicollinearity problems (especially in relationship to one of the temperature variables and sun hours); it could coexist with altitude and degree days.
- Altitude is not likely to present multicollinearity problems.
- The temperature variables are strongly related to one another and will present multicollinearity problems especially with latitude and sun hours; the January temperature should be preferred.
- Degree days will be somewhat collinear with any of the temperature variables (although less so with the July temperature as shown in Fig. 22); it could coexist with latitude, altitude and sun hours.
- Sun hours appears to be the variable with variation least explained by the others but it will present multicollinearity problems when present with latitude and the temperature variables (especially July temperature); sun hours could coexist with degree days.

Looking at building characteristics, the following conclusions may be drawn from Table 5:

- Height proxy is the least likely to present multicollinearity problems, especially with building area.
- Both building area and volume are very highly related to one another and will present multicollinearity problems with height proxy.

5.1. Model estimation

Alternative regression models estimated are shown in Tables 6–8. We start from simple models and we progress to

Table 3
Correlation coefficients (*p*-values in parentheses)

	EFFICIENCY	LATITUDE	ALTITUDE	AMBTEMPJAN	AMBTEMPJUL	DEGRMONTHS	SUNDAYS	M2_1000	M2_1000<70	M3_1000
LATITUDE	-0.342 *(0.002)*									
ALTITUDE	-0.026 *(0.828)*	-0.088 *(0.466)*								
AMBTEMPJAN	0.397 *(0.002)*	-0.878 *(0.000)*	-0.034 *(0.803)*							
AMBTEMPJUL	0.274 *(0.032)*	-0.920 *(0.000)*	0.064 *(0.639)*	0.806 *(0.000)*						
DEGRMONTHS	-0.494 *(0.000)*	0.902 *(0.000)*	0.059 *(0.677)*	-0.909 *(0.000)*	-0.895 *(0.000)*					
SUNDAYS	0.415 *(0.001)*	-0.896 *(0.000)*	0.027 *(0.845)*	0.751 *(0.000)*	0.794 *(0.000)*	-0.823 *(0.000)*				
M2_1000	-0.228 *(0.073)*	-0.097 *(0.448)*	-0.111 *(0.409)*	0.005 *(0.971)*	0.158 *(0.244)*	-0.055 *(0.686)*	0.108 *(0.427)*			
M2_1000<70	-0.070 *(0.587)*	-0.227 *(0.076)*	-0.107 *(0.432)*	0.154 *(0.260)*	0.264 *(0.051)*	-0.101 *(0.464)*	0.237 *(0.081)*			
M3_1000	0.187 *(0.204)*	-0.244 *(0.094)*	-0.073 *(0.640)*	0.148 *(0.320)*	0.347 *(0.017)*	-0.133 *(0.368)*	0.216 *(0.149)*	0.893 *(0.000)*	0.893 *(0.000)*	
HEIGHTPROXY	0.247 *(0.090)*	-0.141 *(0.341)*	-0.104 *(0.507)*	0.064 *(0.671)*	0.269 *(0.068)*	-0.101 *(0.496)*	0.154 *(0.307)*	0.309 *(0.033)*	0.309 *(0.033)*	0.568 *(0.000)*

more inclusive multiple regression models so that we may examine changes in coefficient values or when multicollinearity effects become present.

Table 6 shows models with independent variables selected among environmental factors that we expect to be the strongest predictors. Table 7 adds building characteristics while Table 8 shows models that, in addition to the previous variables, include passive solar technology dummy variables. Underneath the model number in these tables, we show the number of observations (buildings) on which the model was estimated (n) and the number of observations that were omitted due to missing values in some of the variables (n_{M}). Before we embark on a more detailed discussion of alternative models, it must be kept in mind that since these models were estimated on cross sectional (rather than time series) data, relatively low R^2 values in the order of 0.4–0.5 may be regarded as quite satisfactory.

Since degree days (DEGRMONTHS) is both theoretically appealing and the environmental variable most

Table 4
Auxiliary regressions of locational and environmental variables (*t*-values of slope coefficients in parentheses)

	CONSTANT	LATITUDE	ALTITUDE	AMBTEMPJAN	AMBTEMPJUL	DEGRMONTHS	SUNDAYS	s	R^2	R^2 adj.
LATITUDE	69.1	–	-0.00508 *(-4.53)*	-0.581 *(-6.49)*	-0.618 *(-9.10)*	-0.0016 *(-0.11)*	-0.0846 *(-7.25)*	0.967	0.983	0.981
ALTITUDE	4264	-63.7 *(-4.53)*	–	-44.4 *(-3.58)*	-33.8 *(-2.83)*	0.58 *(0.35)*	-4.46 *(-2.44)*	108.3	0.357	0.283
AMBTEMPJAN	63.8	-0.852 *(-6.49)*	-0.00518 *(-3.58)*	–	-0.492 *(-4.14)*	-0.0481 *(-2.94)*	-0.0636 *(-3.41)*	1.17	0.928	0.919
AMBTEMPJUL	83.1	-1.07 *(-9.10)*	-0.00464 *(-2.83)*	-0.579 *(-4.14)*	–	-0.0384 *(-2.07)*	-0.0861 *(-4.61)*	1.270	0.941	0.934
DEGRMONTHS	154	0.17 *(0.11)*	0.0049 *(0.35)*	-3.48 *(-2.94)*	-2.36 *(-2.07)*	–	-0.25 *(-1.43)*	9.953	0.916	0.906
SUNDAYS	494	-6.5 *(-7.25)*	-0.0273 *(-2.44)*	-3.34 *(-3.41)*	-3.84 *(-4.61)*	-0.181 *(-1.43)*	–	8.480	0.876	0.862

Table 5
Auxiliary regressions of locational and environmental variables (t-values of slope coefficients in parentheses)

	CONSTANT	M2_1000	M3_1000	HEIGHTPROXY	s	R^2	R^2 adj.
M2_1000	1.14	–	0.263 *(15.37)*	-0.36 *(-4.25)*	0.508	0.855	0.849
M3_1000	-4.44	3.19 *(15.37)*	–	1.60 *(6.27)*	1.769	0.892	0.887
HEIGHTPROXY	2.69	-0.797 *(-4.25)*	0.292 *(6.27)*	–	0.756	0.517	0.496

strongly associated with energy efficiency, we estimate at first a lean model incorporating degree months as the only explanatory variable (Model M1 in Table 6). As expected, we get a model with a very significant negative coefficient for degree days and a rather low R^2 (0.244) since many more factors determine the energy efficiency of a building; yet it is interesting to note that one fourth of the variability in energy efficiency values in our sample is explained by degree days alone.

Model M2 in Table 6 adds sun hours (SUNDAYS), found to be the most appropriate variable to try with degree days, to the previous specification. Although the fit of the model improves a little (adjusted R^2 increased from 0.23 to 0.247) and the coefficient of sun hours has the expected sign (+), the coefficient of degree days changed from −0.301 to −0.105 and became insignificant possibly due to collinearity with sun hours (indicated by variance inflation factors or VIFs equal to 3.1). Throughout our analysis we regard VIF values less than 5 as somewhat indicative of multicollinearity problems but acceptable, values between 5 and 10 indicating a larger problem but possibly acceptable and values larger than 10 unacceptable [42].

As a last effort at adding a second quantitative environmental variable to degree days, based on our auxiliary regression results, we add ambient temperature in July (AMBTEMPJUL, model M3 in Table 6). The resulting model gives a fit inferior to M2 and about equal to M1 (judging from s, the standard error of the estimate and R^2-adjusted values) and although the coefficient of degree days bears the expected sign (−), that of July temperature appears to be negative, contrary to our expectations and to the sign of the corresponding correlation coefficient. Since VIF values now equal 5, this may be due to collinearity between the two independent variables.

Finally, we add a dummy variable (MEDITERRANEAN) to distinguish between buildings located in the Mediterranean (Greece, Italy, Spain, the south of France and Portugal) and those in the rest of Europe in order to account for climatic conditions that are specific to the Mediterranean region and may not be captured by degree days (e.g. lack of temperature extremes, humidity, breeze); it should be noted that the difference in efficiencies between buildings in the Mediterranean and those in the rest of Europe is statistically significant (two sample $t = 2.65$; $p = 0.10$). The resulting model M4 gives a fit almost identical to M1 although none of

Table 6
Alternative energy efficiency regression models (environmental characteristics)

Model		CONSTANT	LATITUDE	ALTITUDE	AMB-TEMPJAN	AMB-TEMPJUL	DEGR-MONTHS	SUNDAYS	MEDITER-RANEAN	M2_1000	M3_1000	HEIGHT-PROXY	s	R^2	R^2 adj.
M1	a_i	87.5					-0.301						17.475	0.244	0.23
n=57	t *(p)*	16.35 *(0.000)*					-4.21 *(0.000)*								
n_M=20	VIF						–								
M2	a_i	45.9					-0.105	0.327					17.281	0.275	0.247
n=54	t *(p)*	1.92 *(0.060)*					-0.82 *(0.418)*	1.78 *(0.080)*							
n_M=23	VIF						3.1	3.1							
M3	a_i	134				-1.48	-0.502						17.486	0.257	0.229
n=56	t *(p)*	3.91 *(0.000)*				-1.38 *(0.175)*	-3.04 *(0.004)*								
n_M=21	VIF					5.0	5.0								
M4	a_i	75.7					-0.2		8.21				17.472	0.258	0.23
n=57	t *(p)*	5.92 *(0.000)*					-1.62 *(0.111)*		1.01 *(0.317)*						
n_M=20	VIF						3		3						

Table 7
Alternative energy efficiency regression models (environmental and building characteristics)

Model		CONSTANT	LATITUDE	ALTITUDE	AMB-TEMPJAN	AMB-TEMPJUL	DEGR-MONTHS	SUNDAYS	MEDITER-RANEAN	M2_1000	M3_1000	HEIGHT-PROXY	s	R^2	R^2 adj.
M5	a_i	89.2					-0.310			-0.550			17.012	0.308	0.282
n=56	t *(p)*	16.87 *(0.000)*					-4.44 *(0.000)*			-2.23 *(0.030)*					
n_M=21	VIF						1.0			1.0					
M6	a_i	92.3					-0.323			-10.5	2.78		15.257	0.461	0.425
n=48	t *(p)*	16.18 *(0.000)*					-4.67 *(0.000)*			-2.74 *(0.009)*	2.89 *(0.006)*				
n_M=29	VIF						1.1			5.1	5.2				
M7	a_i	83.2					-0.354					3.58	16.013	0.393	0.366
n=48	t *(p)*	9.44 *(0.000)*					-4.96 *(0.000)*					1.62 *(0.112)*			
n_M=29	VIF						1.0					1.0			
M8	a_i	82.9					-0.355			-1.62		4.19	16.060	0.403	0.363
n=48	t *(p)*	9.38 *(0.000)*					-4.96 *(0.000)*			-0.86 *(0.395)*		1.80 *(0.078)*			
n_M=29	VIF						1.0			1.1		1.1			
M9	a_i	71.8					-0.132		15.7	-12.6	2.91		14.764	0.507	0.461
n=48	t *(p)*	6.15 *(0.000)*					-1.13 *(0.266)*		2 *(0.052)*	-3.27 *(0.002)*	3.12 *(0.003)*				
n_M=29	VIF						3.2		3.4	5.5	5.2				
M10	a_i	71.9					-0.248		8.74			3.26	15.961	0.411	0.37
n=48	t *(p)*	5.42 *(0.000)*					-2.12 *(0.039)*		1.14 *(0.261)*			1.47 *(0.149)*			
n_M=29	VIF						2.7		2.8			1.1			

the coefficients is statistically significant and the VIFs equal 3; the coefficient of degree days equals -0.2 (compared to -0.3 in model M1) while the Mediterranean dummy has a coefficient of 8.21 (indicating the average energy efficiency gain for buildings located in the Mediterranean).

All in all, among the models incorporating environmental variables only, we deem that the lean specification represented by M1 is best although we also like model M4 because it appears to be consistent with our expectations (despite the fact that none of the coefficients is statistically significant).

We now proceed to adding building characteristics to our lean model (M1) and possibly to M4. To investigate the effect of building size on energy efficiency, in model M5 (Table 7) we start by adding building area (M2_1000) to degree days and achieve both an improvement in adjusted R^2 (from 0.230 for M1 to 0.282 for M4) as well as statistically significant negative coefficients for both independent variables; the specification appears to be valid since the coefficient of degree days is -0.310, very close to the value -0.301 in model M1, while the coefficient of building area is -0.550, indicating that buildings with larger area tend to be less energy efficient (a plausible finding) and VIFs are unity, indicating absence of collinearity. We conclude that model M5 is an improvement over model M1.

We now consider adding more building characteristics to M5, our best model so far. On statistical grounds alone, replacing building area with volume does not appear to be an attractive idea since building volume is not significantly associated with energy efficiency. Therefore, in model M6, we add building volume to building area and obtain a much better fit (adjusted R^2 equal to 0.425, up from 0.282 in M5, and a significant reduction of s from 17.012 to 15.257) although there is a very large change in the coefficient of building area (from -0.550 in model M4 to -10.5). Although part of this unwelcome change may be due to collinearity between the two building variables, indicated by relatively high VIF values (5.1 and 5.2), we think that the effect of collinearity is not overly large since both coefficients are statistically very significant. The coefficient of building volume is positive (2.78), in agreement with the correlation coefficient between energy efficiency and building volume (0.187), indicating that buildings with larger volume tend to be more energy efficient. Based on

Table 8
Alternative energy efficiency regression models (including passive technology characteristics)

Model		CONSTANT	LATITUDE	ALTITUDE	AMBTEMPJAN	AMBTEMPJUL	DEGRMONTHS	SUNDAYS	MEDITARRAEAN	M2_1000	M3_1000	HEIGHTPROXY	GREENHOUSE	THSTORWALL	SHADING	NATURAIR	DIRPROFIT	SOLWATHEAT	s	R^2	R^2 adj.
M11	a_i	70.4					-0.127		18.9	-12	2.66		1.52	-6.63	-4.43	-1.1	5.16	2.35	15.087	0.557	0.437
n=48	t *(p)*	3.68 *(0.001)*					-1.03 *(0.312)*		2.27 *(0.029)*	-2.94 *(0.006)*	2.64 *(0.012)*		0.29 *(0.770)*	-1.34 *(0.187)*	-0.84 *(0.407)*	-0.09 *(0.927)*	0.68 *(0.500)*	0.29 *(0.773)*			
n_M=29	VIF						3.5		3.6	5.8	5.8		1.4	1.2	1.5	1.3	1.1	1.3			
M12	a_i	76.7					-0.147		18	-11.7	2.64		0.18	-6.80	-4.37				14.628	0.55	0.471
n=48	t *(p)*	6.02 *(0.000)*					-1.26 *(0.214)*		2.26 *(0.030)*	-2.99 *(0.005)*	2.73 *(0.009)*		0.04 *(0.970)*	-1.45 *(0.155)*	-0.90 *(0.372)*						
n_M=29	VIF						3.2		3.6	5.8	5.7		1.2	1.2	1.3						
M13	a_i	74.8					-0.14		16.6	-11.8	2.74			-7.60					14.427	0.54	0.486
n=48	t *(p)*	6.48 *(0.000)*					-1.23 *(0.227)*		2.15 *(0.037)*	-3.11 *(0.003)*	2.99 *(0.005)*			-1.74 *(0.089)*							
n_M=29	VIF						3.2		3.4	5.6	5.3			1							

these findings, we tend to believe that, despite some collinearity between building area and volume, we have encountered a real negative effect of building area and a real positive effect of building volume on energy efficiency.

An alternative way of incorporating the effect of both building characteristics would be to include the height proxy variable (HEIGHTPROXY) either by itself (model M7) or with building area (model M8). Both of these models give better fits than M5 (adjusted R^2 values equal to 0.366 and 0.363 in M7 and M8 correspondingly, up from 0.282 in M5) although not as good as M6 that includes both area and volume ($R^2 = 0.425$); on the other hand, the coefficient of height proxy in M7 is not significant while the coefficient of building area in M8 has also become insignificant (maintaining the correct sign). Among M7 and M8 which perform similarly, we prefer the leaner specification of M7 that accounts for both building characteristics without any collinearity problems and, due to the positive coefficient of height proxy, implies an interesting (if weak) effect that taller and leaner structures are more energy efficient. Therefore, we think that model M7 is a better model than M5 (and possibly M6).

In model M9 we make another effort to incorporate the effect of unaccounted climate characteristics by adding the Mediterranean dummy to M6 and get our best model fit so far. R^2 adjusted increases to 0.461 (s is reduced to 14.764), the coefficients of both building volume and area remain statistically very significant (and relatively close in value to those in M6) and the coefficient of the Mediterranean dummy is close to 95% significance; on the other hand, the coefficient of degree days changes to −0.132 and becomes insignificant possibly due to collinearity with the Mediterranean dummy (VIFs equal to 3.2 and 3.4 correspondingly). To avoid collinearity between building area and volume we also try model M10 in which we replace building area and volume with height proxy. R^2 adjusted falls to 0.37 (s equal to 15.961) and although VIFs are relatively low, the coefficients of the Mediterranean dummy and height proxy are insignificant. Therefore, despite the minor problems in M9, since all the variables enter the equation with correct signs and most coefficients are statistically significant, we think it is a good model.

In conclusion, we think that our best model thus far is model M9, which accounts for the effect of degree months, location in the Mediterranean, building area and building volume. We keep in mind that in incorporating a Mediterranean dummy we allow a degree of overlap with degree months but we feel certain that climatic conditions endemic in the Mediterranean region exert additional influence on the determination of energy efficiency. We also keep in mind that building volume and building area are collinear but it appears that the problem is not so severe as to impair our specification; replacing these variables with their ratio (height proxy) avoids collinearity problems but the effect is not as statistically significant.

We now turn our attention to the group of dummy variables representing the presence (or absence) of specific passive solar technologies. We remember that due to their frequency distribution in our sample, only greenhouse, thermal storage wall, shading and possibly natural aeration, direct profit and solar water heater will be used. Alternative models are shown in Table 8.

At first we add to M9, our best model thus far, all dummy variables with enough non-missing values. The model fit is quite good, as expected with so many independent variables, although not as good as that of M9. The coefficient of degree months changes from −0.132 (in M9) to −0.127 and remains insignificant (albeit with the correct sign). The coefficient of the Mediterranean dummy is increased from 15.7 (in M9) to 18.9 and becomes significant ($p = 0.029$), showing location in the Mediterranean area to exert the strongest influence on energy efficiency among all independent variables examined. Building area and volume have expected coefficient signs and values relatively close to those of M9 (both very significant). There are some rather surprisingly issues with the passive technology dummies. First of all, only three of these (greenhouse, direct profit and solar water heater) enter the regression equation with a positive sign (i.e. positive influence on energy efficiency); the other three (thermal storage wall, shading and natural aeration) have negative coefficients. Yet, none of the six coefficients is statistically significant although that of thermal storage wall is more significant than the others ($p = 0.187$).

Since we get insignificant results, we decide to drop the natural aeration, direct profit and solar water heater from further consideration (since they only have few values in one of the two categories) and, since VIF values are low, maintain greenhouse, thermal storage wall and shading. Thus, we obtain model M12. As indicated both by s and R^2 adjusted, M12 is better than M11. Of the three remaining passive technology dummies, thermal storage wall is the most significant ($p = 0.155$). Retaining this dummy, we obtain model M13 that is a further improvement from M11 (again judging from s and R^2 adjusted). The coefficient of degree months has become −0.14 ($p = 0.227$) while that of the Mediterranean dummy 16.6 ($p = 0.037$); this compares to a coefficient of degree days about equal to −0.3 when it was the only environmental independent variable and we think this change is reasonable (although some of it is caused by correlation among degree days and the Mediterranean dummy). The coefficients of building area and volume are equal to −11.8 and 2.64, respectively, both very significant; these values compare well with those of models M6 and M9.

We are intrigued by the negative coefficient of the thermal storage wall dummy (−7.6) that is significant at a 90% confidence level. This implies that the presence of thermal storage walls in a bioclimatic building may in fact reduces overall energy efficiency; this may be possible if energy efficiency losses by the presence of thermal storage walls in the summer, for instance, are greater than energy efficiency gains in the winter. Given that similar negative coefficients were found in the case of shading and natural aeration, we think that this implication is serious enough to warrant further investigation with a larger data set incorporating more information.

In concluding our analysis, we propose model M13, shown below, as our best model.

$$\begin{aligned}\text{EEFFICIENCY} = {} & 74.8 - 0.14\,\text{DEGRMONTHS} \\ & + 16.6\,\text{MEDITERRANEAN} \\ & - 11.8\text{M2\_1000} + 2.74\text{M3\_1000} \\ & - 7.6\,\text{THSTORWALL} \\ & (s = 14.427, R^2 = 0.54)\end{aligned}$$

As indicated by R^2, M13 explains 54% of the variation in energy efficiency values, a satisfactory percentage if one considers that this was a cross sectional study on a relatively small sample as well as that, no doubt, many more factors determine energy efficiency than those included in our data.

6. Conclusions and recommendations

The analysis carried out in this work leads to the following conclusions:

- Environmental conditions (as measured by degree days and location within the Mediterranean) are the most important determinant of energy efficiency. On one hand, degree days that determine the need for heating, are inversely related to energy efficiency (more energy efficient buildings are built in warmer climates); according to our best model (M13), approximately 50 degree months (about 1500 degree hours) decrease energy efficiency by 7%. On the other hand, the location of building within the Mediterranean adds an average of about 17% to energy efficiency.
- Building area and volume have a significant impact on energy efficiency. On one hand, buildings with larger floor space are characterized by smaller energy efficiency values (about 12% lower for every 1000 m^2). On the other hand, buildings with larger volume rather surprisingly tend to be more energy efficient, adding about 2.7% for every 1000 m^3. Replacing both of these variables with their ratio (volume over area, to avoid collinearity) confirms that buildings with a larger ratio of volume to floor space (sort of a proxy for building height) are characterized by larger performance. In other words, it appears that taller and narrower buildings are more energy efficient, an interesting finding since it does not appear to be caused by the employment of different passive solar technologies (although it may well be caused by using more such technologies).
- Finally, the use of different passive technologies does not seem to affect energy efficiency significantly (although, sadly, we did not have any data on how these technologies were used and maintained). Since only three technology dummy variables had sufficient nonzero values, we were able to conclude that the presence of thermal storage walls

decreased energy efficiency (at a 90% significance level) by 7.6%. Shading was also found to exert a negative influence on energy efficiency but its coefficient was not significant. We think that while the owner of a plot who wishes to built a bioclimatic house and the architect who designs it, may share the wish to add selected technologies that increase convenience in certain times of the year, in fact some of these technologies may increase overall energy consumption and therefore CO_2 emissions; in fact, heating has traditionally been regarded as a priority over cooling [15] and this may very well explain why thermal storage walls appear to reduce energy efficiency. All in all, the fact that some passive technologies may in fact decrease overall energy efficiency (by adversely affecting it during summer months for example) is an intriguing finding that needs verification with a bigger data set that would include more information.

The implications of our work concern architects and engineers involved in the design and construction of bioclimatic houses, their prospective clients as well as policy makers. On one hand, the model developed is a novel tool that may be used by architects and engineers to predict energy efficiency for buildings in the design phase. On the other hand, it may be of use to government and institutional bodies that control and regulate construction on a regional or national level since the model may be used to predict aggregate energy savings and reduction of CO_2 emissions and, thereby, target new regulations more accurately; interestingly, Steele [43] as quoted by Knowles [44], warns that bioclimatic or sustainable architecture will eventually ‘‘be forced upon architects’’ by an ‘‘overwhelming confluence of ecological, social and economic forces.

Suggestions for further research include:

- More specific information on individual buildings needs to be collected such as urban or suburban location; street and building orientation; orientation, number and area of openings (doors and windows); number of floors; type of roof.
- More study needs to be carried out on the effect of passive solar technologies since important information (such as number, area or volume of passive elements) was lacking in our data set; yet, based on our experience with gathering these data, procuring such detailed information for individual buildings is a non trivial task that requires a significant investment of time.
- Cluster analysis could be used to confirm grouping of buildings into categories such as Greece, rest of Mediterranean, rest of Europe. Such an effort would be more useful if a larger data set with more information (as outlined in previous suggestion) became available. In such a case, models similar to M13 could be run on each group separately in order to compare the effect of each independent variable. Also, we would be able to understand better the effect of specific technologies (such as thermal storage walls) in environments of specific bioclimatic type (such as thermo, meso-Mediterranean or supra-Mediterranean).
- On the other hand, it would be interesting to analyze a more homogeneous group of buildings, houses for example, possibly with the additional information proposed in previous suggestions.
- Finally, we expect the way a bioclimatic buildings is used to be a major determinant of energy efficiency. When users are careless (for example, in failing to close openings, not using tents and drapes, failing to maintain systems) energy savings are not realized. Educated and mindful users help realize the full energy savings potential of a bioclimatic structure. While gathering actual usage information should be quite difficult, interviewing users to check their education level regarding bioclimatic technologies, document their daily practices in using the building and assess their satisfaction with its performance, should render interesting information that would allow the development of a better model.

Acknowledgments

We are thankful to Dr. George Mavrommatis, former Director of the Institute of Mediterranean Forest Ecosystems of the National Agricultural Research Foundation, for his valuable comments on a preliminary draft of this paper.

References

[1] E. Georgiadou, Bioclimatic Design—Clean Building Technologies [in Greek], Paratiritis (Observer), Thessaloníki, 1996.
[2] M. Karavasili, Buildings for a Green World [in Greek], πSystems International, Athens, 1999.
[3] A. Magliocco, A. Giachetta, Requalification of Public Residential Buildings with Bioclimatic Approach, DIPARC Department, Faculty of Architecture of Genova, 1999 (http://www.iris.ba.cnr.it/sksb/PAPERS/17-05o.pdf).
[4] M. Karavasili, Heating–cooling, Weekly Bulletin, Technical Chamber of Greece, issue 2125, 6th November 2000.
[5] P. Smith, C.A. Pitts, Concepts in Practice—Energy, Building for the Third Millennium, Batsford, Britain, 1997.
[6] D. Radovic, Bioclimatic design as the core of environment programmes, Energy and Buildings vol. 23 (1996) 271–275.
[7] C. Gallo, M. Nicoletti, P.C. von Seidlein, D. Zivas, Solar Buildings: European Student's Competition for the Design of Solar Buildings 1995–1996, G. Falconi (Ed.), Gancemi Editori, 1997.
[8] A. Zain-Ahmed, K. Sopian, M.Y.H. Othman, A.A.M. Sayigh, P.N. Surendran, Daylighting as a passive solar design strategy in tropical buildings: a case study of Malaysia, Energy Conversion and Management vol. 43 (2002) 1725–1736.
[9] N.M. Nahar, P. Sharma, M.M. Purohit, Performance of different passive techniques for cooling of buildings in arid regions, Building and Environment vol. 38 (2003) 109–116.
[10] A. Donald, Putting it together: whole buildings and a whole buildings policy, Renewable Energy Policy Project no. 5 (1998).
[11] Anonymous, Revision of regulation of heat insulation and rational use of energy in the buildings—regulation plan [in Greek], Weekly Bulletin, Technical Chamber of Greece, vol. 1745, 25th January 1993.
[12] Government Newspaper, 21475/4707, 19th August 1998.

[13] A.N. Tombazis, Recent works of A.N. Tombazis and associates architects, Renewable Energy vol. 15 (1998) 72–77.
[14] Y. Etzion, D. Pearlmutter, E. Erell, I.A. Meir, Adaptive architecture: integrating low energy technologies for climate control in the desert, Automation in Construction vol. 6 (1997) 417–425.
[15] N. Cardinale, M. Micucci, F. Ruggiero, Analysis of energy saving using natural ventilation in a traditional Italian building, Energy and Buildings vol. 35 (2004) 153–159.
[16] Center of Renewable Energy Sources (CRES), Bioclimatic Architecture—Applications in Greece [in Greek], 1992.
[17] S.A. Kalogirou, M. Bojic, Artificial neural networks for the prediction of the energy consumption of a passive solar building, Energy vol. 25 (2000) 479–491.
[18] M. Wachbergen, Utilization of Solar Energy in Building Construction [in Greek], Giourdas Editions, 1988.
[19] Institute of Archaeology, Zippori in the Roman Period, The Hebrew University of Jerusalem (http://www.hum.huji.ac.il/archaeology/zippori/RomanSeph.htm, accessed June 2004).
[20] Anonymous, The History of Solar, Energy Efficiency and Renewable Energy, US Department of Energy (www.eere.energy.gov/solar/pdfs/solar_timeline.pdf, accessed June 2004).
[21] J. Perlin, K. Butti, A Golden Thread—2500 Years of Solar Architecture and Technology, Van Nostrand Reinhold Company, New York, 1980.
[22] Anonymous, NREL Overview, National Renewable Energy Laboratory (http://www.nrel.gov/overview.html, accessed June 2004).
[23] Anonymous, Solar Energy Research Facility, Golden CO, National Renewable Energy Laboratory (http://www.nrel.gov/buildings/highperformance/serf.html, accessed June 2004).
[24] N. Zografakis, Technologies for rational use and savings of energy in buildings, Energy [Greek], vol. 62, 112–114, November–December 2000.
[25] D.L. Loveday, K.C. Parsons, A.H. Taki, S.G. Hodder, Displacement ventilation environments with chilled ceilings: thermal comfort design within the context of the BS EN ISO7730 versus adaptive debate, Energy and Buildings vol. 34 (2002) 573–579.
[26] S. Heidari, S. Sharples, A comparative analysis of short-term and long-term thermal comfort surveys in Iran, Energy and Buildings vol. 34 (2002) 607–614.
[27] S. Yannas, Solar Energy and Housing Design—Volume I, Principles, Objectives, Guidelines, Architectural Association, London, 1994.
[28] F. Kavalari, Heating–air conditioning–saving energy—intelligent buildings, Weekly Bulletin, Technical Chamber of Greece, vol. 2172, 29th October 2001.
[29] Regulating Authority for Energy (RAE), The Energy System in Greece [in Greek] (http://www.rae.gr/energysys/main.htm, accessed June 2004).
[30] J. Paravantis, Energy savings in buildings: heating and passive cooling [in Greek], Energy [in Greek], vol. 17, 49–59, November 1995.
[31] E. Athanasakou, Solar passive systems and technologies [in Greek], Energy [in Greek], vol. 24, 55–66, December–January 1996–1997.
[32] V. Badescu, B. Sicre, Renewable energy for passive house heating—Part I: Building description, Energy and Buildings vol. 35 (2003) 1077–1084.
[33] D. Pimentel, R. Rodrigues, T. Wang, R. Abrams, K. Goldberg, H. Staecker, E. Ma, L. Brueckner, L. Trovano, C. Chow, U. Govindarajulu, S. Boerke, Renewable energy: economic and environmental issues, BioScience vol. 44 (no. 8) (1994).
[34] A. Dimitriadis, Thermal behaviour of solar passive buildings in Greece and energy savings—Part A: Energy savings, Technika Chronika [In Greek], July–August 1989.
[35] C. Tantasavadsi, J. Srebric, O. Chen, Natural ventilation design for houses in Thailand, Energy and Buildings vol. 33 (2001) 815–825.
[36] T. Herzog (Ed.), Solar Energy in Architecture and Urban Planning, Prestel, 1996.
[37] H. Coch, Chapter 3: Bioclimatism in vernacular architecture, Renewable and Sustainable Energy Reviews 1 2 (1998) 67–87.
[38] M. Karavasili, Heating–air conditioning [in Greek], Weekly Bulletin, Technical Chamber of Greece, vol. 2125, 6th November 2000.
[39] M. Bodart, A. Herde, Global energy saving in offices buildings by use of daylight, Energy and Buildings vol. 34 (2002) 421–429.
[40] T.R. Oke, Street design and urban canopy layer climate, Energy and Buildings vol. 11 (1988) 103–113.
[41] C. Ratti, D. Raydan, K. Steemers, Building form and environmental performance: archetypes, analysis and an arid climate, Energy and Buildings vol. 35 (2003) 49–59.
[42] A.H. Studenmund, Using Econometrics: A Practical Guide, fourth ed. Pearson Addison Wesley, 2000.
[43] J. Steele, Sustainable Architecture, McGraw Hill, New York, 1997.
[44] R. Knowles, The solar envelope: its meaning for energy and buildings, Energy and Buildings 35 (2003) 15–25.