Quantifying energy demand in mountainous areas

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Abstract. Despite their rich energy renewable potential, mountainous areas suffer from energy poverty. A viable solution seems to be the radical turn towards renewable resources. Any tailor-cut energy planning for mountainous areas presupposes the adequate estimation of the energy demand of buildings, which in this case is hindered by the lack of long-term meteorological data, especially in remote, high altitude areas. In this paper four case studies, namely Switzerland, Austria, Greece and north Italy, are examined, applying the method of degree-days. The scarcity of meteorological stations at higher altitudes has been overcome by calculating the lapse rates (decrease of surface temperature with altitude) for each case, which were found to vary from the common "rule" of 6.5°C/km. Based on these findings, the air temperatures of all remote, mountainous spots can be calculated, and, therefore, the estimation of the energy needs of buildings has been provided, with a high level of accuracy.

Keywords: energy demand; mountainous; renewable; degree-days; lapse rate; altitude; temperature

1 Introduction

The concept of energy crisis lies in the correlation between energy stocks, which tend to decrease, energy consumption requirements which tend to increase and environmental impacts of energy utilization. Fossil fuels reserves are finite, as non-renewable sources, while global energy demand and consumption are constantly increasing. At the same time, the excessive use of fossil fuel resources cause high rates emissions of gaseous pollutants, contributing to climate change. Overall, this trend constitutes a crucial social, economic, political and environmental issue. In this regard, renewable energy resources seem to be the best alternative to the whole energy problem, towards sustainable development.

Mountains are closely related to renewable energy resources. In fact, mountainous terrain along with high-altitude climate, create favorable conditions for the existence of rich renewable energy potential [1,2]. Specifically, both wind speed and incident solar radiation increase versus altitude, and therefore, mountainous areas are usually rich in wind and solar energy resources. Mountainous areas are richer in water potential as well, because of the increasing rainfall and snowfall with altitude. Moreover, many mountain ranges are covered by extensive forests, enriching them with high quantities of biomass.

As a consequence, many opportunities for renewable energy production in mountains are offered. For example, despite the widespread perception of the last decades, that photovoltaics are not suitable for mountainous areas, it is proved that their efficiency increases with altitude, because of the higher incident solar radiation and the prevailing lower temperatures [3]. Water resources, combined with steep slopes of mountainous terrain favor the installation of hydroelectric energy plants. More specifically, regarding hydroelectric power generation, the high drop height of highlands is critical, since it increases the efficiency of the investment [4,5]. Moreover, forest biomass found in mountains is an important renewable energy resource for thermal energy production.

Overall, it seems that a mountainous area is more possible to have higher renewable energy potential, compared to its nearest lowland [3]. As a result, the exploitation of renewable energy sources (RES) can be the answer to the energy poverty issue, which is known to be a vital problem in mountains, along with a major production activity, boosting local incomes. A representative example is the case of Wildpoldsried, a small mountainous town located in the Bavarian Alps, Germany, at 720 m altitude, which is known as the “energy village”. This town began its first RES applications in 1997, mainly through wind turbines and biomass digesters for cogeneration of heat and power. Nowadays, this effort has evolved into a real local industry of solar panels, biogas digesters, windmills, small hydro power plants and a district heating network supplied with biomass. In this way, the town produces five times the energy it consumes, along with a significant annual amount of revenue, being counted up to 4.0 million Euro, while the town’s carbon footprint has been reduced by 65 percent.

In any case, the first step for any energy planning within a region is the estimation of its energy needs. The exact determination of the current energy demand is the main prerequisite for the integration of renewable energy into existing energy production systems. However, this is a difficult issue, regarding mountainous areas. The scarcity of meteorological stations at high altitudes (lack of access to long-term meteorological data) has formed a serious obstacle to studying the energy demand variation in mountains. The only adequate network of mountainous meteorological stations is found in high European mountain ranges such as the Alps and in northwestern America. Till now, qualitative estimations about the high energy demand of mountainous areas have been mostly expressed, based on the cold climatic conditions prevailing, not supported by specific quantitative data though. Only a few references, e.g. [1], [6], including quantitative facts have been detected.

In this paper, a methodological tool for quantifying the energy demand of the building sector of four mountainous areas, namely Austria, Switzerland, Greece and north Italy is given.

2 Materials and Methods

Energy demand of buildings has been calculated according to the method of degree-days. The method of degree-days is one of the simplest and most recognized methods for the energy analysis of the building sector [7]. Heating and cooling degree-days (HDDs and CDDs) are quantitative indicators, based on temperature data, designed to reflect the heating and cooling energy needs of a building. Actually, a degree-day symbolizes the quantity and duration at which the external temperature is above or below a defined threshold value, known as base temperature [8,9,10].

The base temperature is a critical parameter for the degree-days estimation. It is not equal to the interior desired temperature, while it depends on the characteristics of the building examined. However, regarding that technical characteristics vary between different buildings and different areas, a stable value of the base temperature is usually chosen for a specific area, so that its energy demand can be quantified. Since there are no generalized, default values for the base temperature selection, the final choice lies on individual researchers' estimation, taking into consideration the special climatic and temperature conditions of the region examined.

The main advantage of the degree-days methodology is that degree-days are based only on air temperature data. The simplest technique for calculating degree-days uses the difference of the mean daily air temperature from the chosen base temperature [11,12]. However, since temperature data are usually given on a monthly basis, another method is the most commonly used for calculating degree-days, the Erbs methodology [13], based on monthly temperature data and on the standard deviation of the average daily temperature of the month.

Yet, temperature data, let alone degree-days data, are not usually available in the case of high altitudes, considering the sparse network of mountainous meteorological stations. This difficulty can be overcome by introducing the surface temperature lapse rate value (decrease of surface temperature with altitude). Specifically, lapse rate is produced by quantifying temperature distribution with altitude, thus giving air temperature at a given altitude, in a simple manner. According to the International Standard Atmosphere [14], which regards the Earth's atmosphere as an ideal gas, temperature decreases with altitude at the constant rate of 6.5°C/km, so it can be easily calculated at a given altitude by the following Equation:

$$T=To-6.5xh/1000[°C] \quad (1)$$

where,

T_o: temperature at sea level, defined at 15°C

h: elevation (m)

In this direction, numerous references have been detected, reporting that air temperature of any region can be calculated combining the above atmospheric model with the available temperature data of the nearest meteorological station. The equation then is transformed as follows [15]:

$$T2=T1-6.5x(h2-h1)/1000[°C] \quad (2)$$

where,

T2: temperature of the region examined (°C)

T1: temperature of the nearest region – reference region (°C)

h2: elevation of the region examined (m)

h1: elevation of the nearest region – reference region (m)

This standard lapse rate value (6.5°C/km) has been used in several studies, e.g. [16,17,18,19]. However, it has been a subject of dispute between researchers, stating that it varies considerably across different areas. Especially, researchers focusing on mountainous areas by conducting experimental studies with the use of temperature sensor networks, support that the often used values of 6.0-6.5°C/km are not representative of the real conditions, and, even more, that they vary significantly in the case of different mountainous areas, such as the Appalachian mountains [20], the Alps [21], the central Rocky Mountains [22] and elsewhere. In these cases, it is supported that the mean annual lapse rates vary between 3.9°C/km and 5.2°C/km [23]. As a result, defining real lapse rate values in terms of the specific geographical region examined can be very important in energy planning.

After defining a distinct lapse rate value for each one of the cases studied, the mean monthly air temperatures of each remote mountainous station over 600 m are calculated, according to Equation (2), by applying the air temperature values of the nearest station below 600m altitude as reference values and the distinct lapse rate value of each region instead of the 6.5°C/km value. In particular, the Equation (2) is transformed as follows:

$$T2 = T1 - (\text{lapse rate}) \times (h2 - h1)/1000 \ [°C] \quad (3)$$

Since air temperatures are calculated for any remote mountainous spot, degree-days, and, subsequently, energy needs of the buildings can be then calculated. Heating and cooling energy needs of a building are proportional to the existing climatic conditions, expressed by degree-days, and to the technical characteristics of the building shell, expressed by the heat transfer coefficient. The annual energy demand of buildings for heating is given by Equation (4) and the corresponding demand for cooling by Equation (5).

$$Qh = Htot \times HDD \times 24/1000 \ [KWh] \quad (4)$$

$$Qc = Htot \times CDD \times 24/1000 \ [KWh] \quad (5)$$

where,

Htot: total heat transfer coefficient because both of convection and ventilation (W/°C)

HDD: heating degree-days (°C*days)

CDD: cooling degree-days (°C*days)

Taking into account that the technical features of the building shell vary considerably from one place to another, the heat transfer coefficient included in the energy demand calculation can be kept stable within a geographical area, leaving degree-days as the only factor defining the variation of energy demand from place to place. In this case, the proportion of thermal to cooling energy demand equals to this of HDD to CDD [3]:

$$Qh/Qc=HDD/CDD \quad (6)$$

Furthermore, the variation of degree-days directly reflects the variation of energy needs within a region, by keeping constant the technical characteristics of the buildings. According to [24], the percentage variation of the heating, cooling, as well as the total energy demand of the same building, located at different altitudes, can be calculated:

$$(Qh2-Qh1)/Qh1=(HDD2–HDD1)/HDD1\ [\%] \quad (7)$$

$$(Qc2-Qc1)/Qc1=(CDD2–CDD1)/CDD1\ [\%] \quad (8)$$

$$(Qtot2-Qtot1)/Qtot1=[(HDD2+CDD2)-(HDD1+CDD1)]/(HDD1+CDD1)\ [\%] \quad (9)$$

To sum up, the main steps of the methodology are:

- Development of a long-term temperature database for all the cases studied, namely Switzerland, Austria, Greece and north Italy, making the analysis more reliable. More specifically, 88 meteorological stations with a 30-year monthly temperature record were used for the case of Switzerland, 63 stations with a 110-year record for the case of Austria, 37 stations with a 107-year record for north Italy and 100 stations with at least a 10-year record for Greece. The meteorological stations list includes a wide range of altitudes. Figure 1 depicts the geographical distribution of the meteorological stations throughout the Alpine region examined.
- Calculation of the monthly and the annual heating and cooling degree-days for all meteorological stations of the countries examined, according to the Erbs method. The HDDs and CDDs were calculated after selecting the appropriate base temperatures that simulated more realistically each country's climatic conditions. For the case of heating, the base temperatures chosen were 14°C for Switzerland and Austria and 16°C for north Italy and Greece while for the case of cooling, the base temperatures chosen were 18°C for Switzerland and Austria, 20°C for north Italy and 22°C for Greece.
- Quantification of temperature distribution with altitude for all the cases examined, diagrams and calculation of the corresponding lapse rate values through simple regression models.
- Calculation of air temperatures of all mountainous meteorological stations over 600 m, based on the corresponding lapse rate value and on the air temperature value of the nearest station below 600 m.
- Re-calculation of heating degree-days for the above mountainous stations, based on the new air temperatures calculated. Comparing results with the first ones calculated in step 2.
- Determination of the variation of the energy demand throughout the four regions.

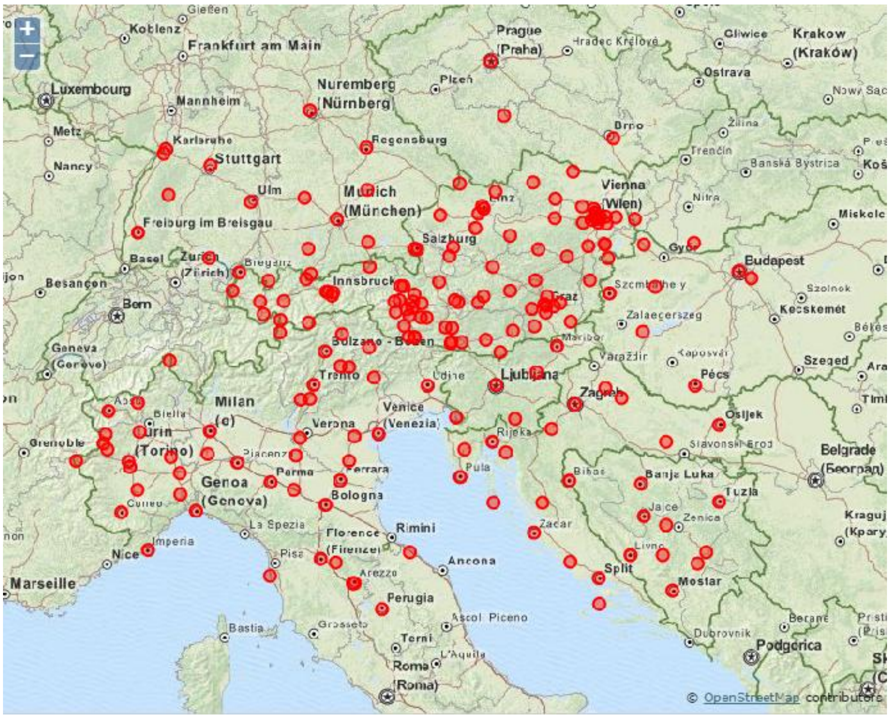

Fig. 1. Geographical distribution of meteorological stations throughout Austria, Switzerland and north Italy (Source: http://www.zamg.ac.at/histalp/dataset/station/osm.php)

3 Results and Discussion

Temperature distribution with respect to altitude is depicted in Figures 2, 3, 4, 5 and 6 for Austria, Switzerland, Greece, north Italy and all cases included, respectively.

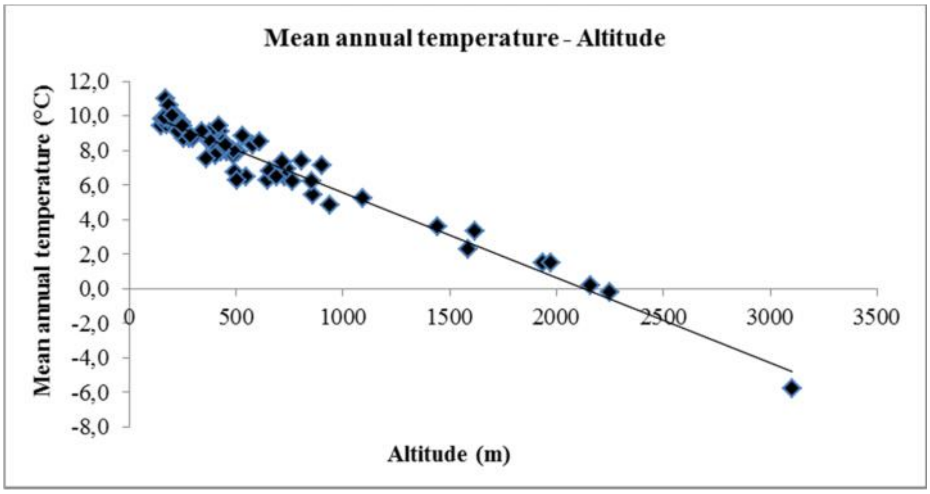

Fig. 2. Temperature distribution with respect to altitude for Austria

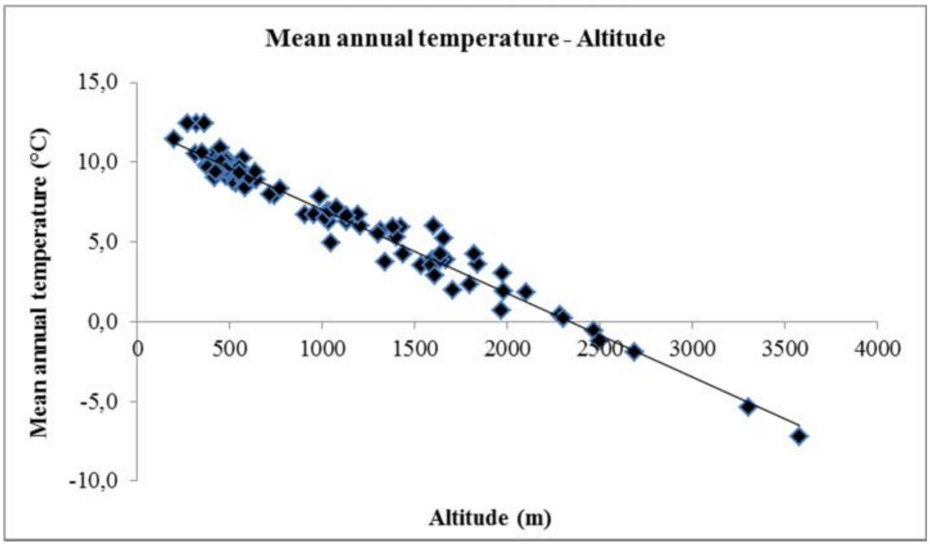

Fig. 3. Temperature distribution with respect to altitude for Switzerland

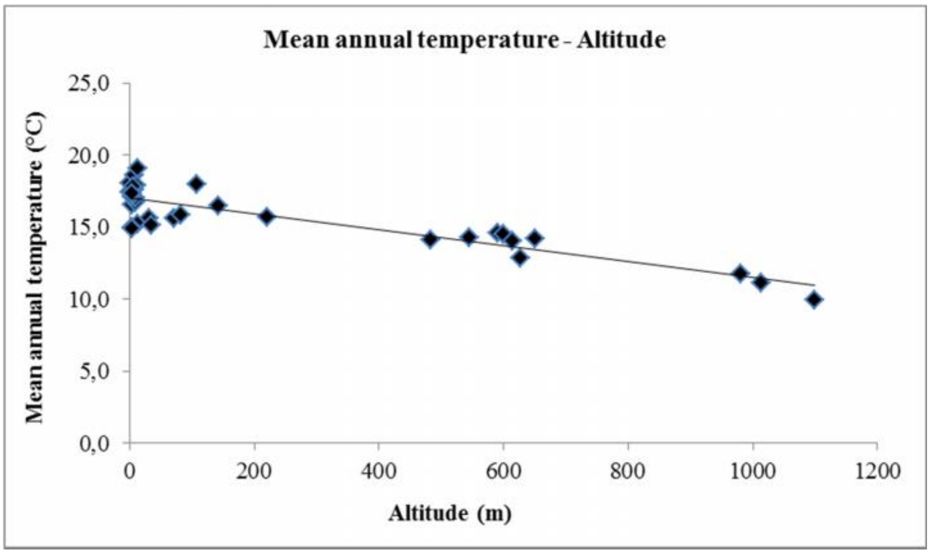

Fig. 4. Temperature distribution with respect to altitude for Greece

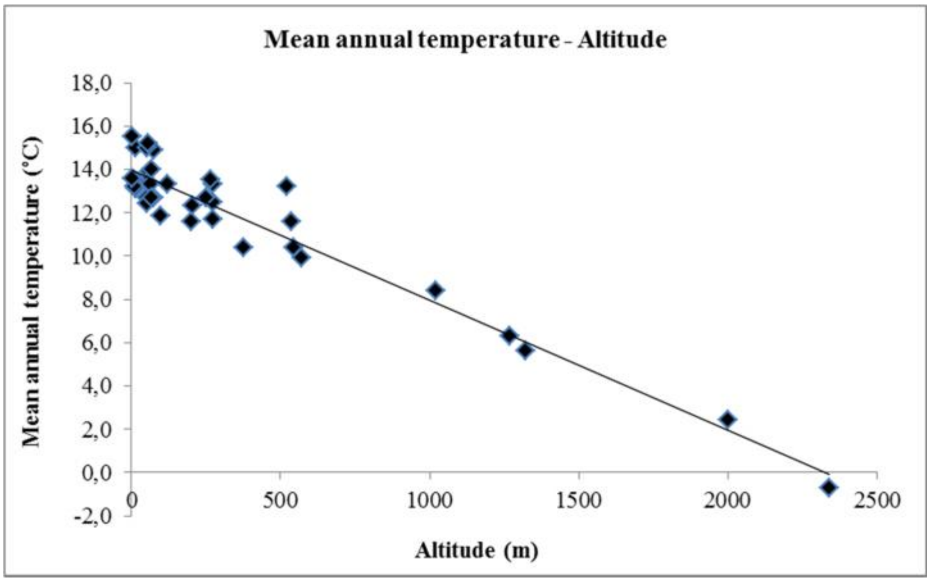

Fig. 5. Temperature distribution with respect to altitude for north Italy

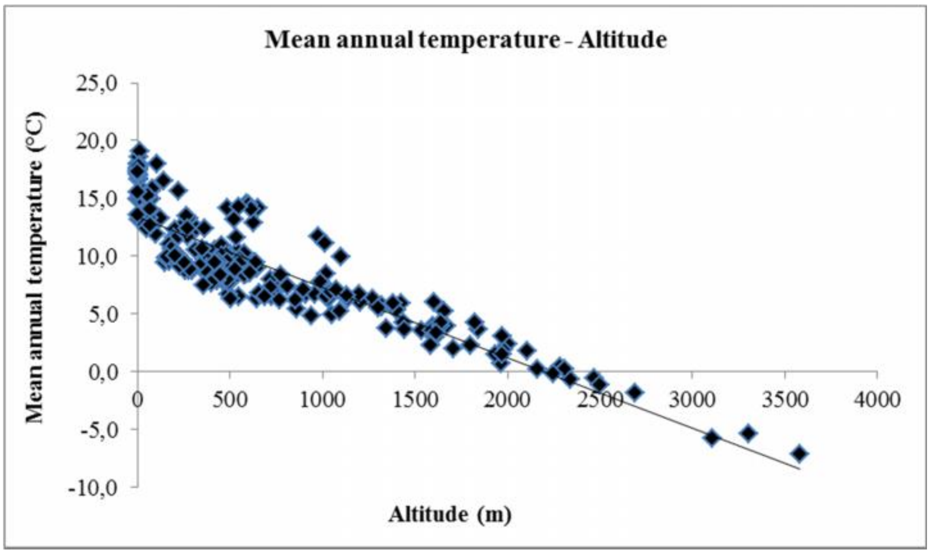

Fig. 6. Overall temperature distribution with respect to altitude for all cases examined

As shown in Figures 2 to 6, air temperature is linearly and negatively related to altitude. More specifically, air temperature decreases versus altitude at a constant rate for all cases. In order to calculate lapse rates, the equations correlating mean annual air temperature with altitude are formed for each country, by performing simple regression analysis. The lapse rate value is the slope of each regression line.
The corresponding equation for Austria is:

$$T = -0.0049xh+10.453 \; [°C] \tag{10}$$

The lapse rate value for Austria is 4.9°C/km.
The equation for Switzerland is:

$$T=-0.0052xh+12.281 \; [°C] \tag{11}$$

The lapse rate value for Switzerland is 5.2°C/km.
The equation for Greece is:

$$T=-0.0055xh+17.020 \; [°C] \tag{12}$$

The lapse rate value for Greece is 5.5°C/km.
The equation for north Italy is:

$$T=-0.0060xh+13.972 \; [°C] \tag{13}$$

The lapse rate value for north Italy is 6.0°C/km.
The equation for the overall distribution examined is:

$$T=-0.0061xh+13.375 \; [°C] \tag{14}$$

The corresponding lapse rate value is 6.1°C/km

Indeed, it is proved that the lapse rate value concerning the sum of cases (6.1°C/km) approaches the common “rule” of 6.5°C/km whereas it varies significantly when focusing on individual mountainous countries or regions, ranging from 4.9°C/km to 6.0°C/km.

The mean monthly air temperatures of each remote mountainous station over 600 m are then calculated, according to Equation (3). It should be clarified that the Equations (10) to (13) can estimate the mean annual air temperature at any location within the countries examined but this annual value is useless regarding the degree-days calculation, and consequently, the energy demand calculation. These calculations require monthly temperature data and the Equation (3) is the solution to this problem, as allowing the use of monthly values. So, after assessing the monthly air temperatures for the above mountainous stations, monthly and annual heating degree-days are calculated.

Table 1 shows a representative example of the methodology followed, regarding north Italy. More specifically, the monthly air temperatures, as well as the HDDs of the meteorological station “Predazzo” at 748 m were calculated, based on the given air temperatures of the nearest station “Bozen/Bolzano” at 272 m, within 48 km distance. The air temperatures of “Bozen/Bolzano” were used as reference values, and the lapse rate of north Italy used, is equal to 6.0°C/km, according to Equation (13). The missing data of HDDs in July and August mean that no heating is required during these months. The method gives low deviations between the new calculated HDD values and the “real” HDD values, with a mean monthly value of 12 percent and an annual value of 9 percent. It is noted that the highest value of the HDDs deviation is observed in June, as this month marginally requires heating, and, therefore, the HDDs, even the “real ones” are almost insignificant for this month. As a result, the method provides reliable results for the HDDs in north Italy.

Table 1. Air temperatures and HDDs in Predazzo, Italy, based on the proposed method

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
T (Predazzo)	-3,8	-1,0	3,8	8,0	12,3	15,8	18,0	17,4	13,7	7,7	1,2	-3,0	7,5
model HDDs	614	475	378	240	122	36	-	-	80	257	443	589	3233
“real” HDDs	531	434	377	257	141	57	-	-	82	207	368	500	2956
HDDs deviation	15%	9%	0%	7%	13%	37%	-	-	2%	24%	20%	18%	9%

Applying this method to all mountainous stations over 600 m in Austria, Switzerland, Greece and north Italy, it is found that the mean deviation between the calculated and the “real” annual HDDs is equal to7 percent, while this of the monthly HDDs equals to 17 percent, meaning that the method provides very good estimations for the HDDs. Furthermore, it should be noted that only heating degree-days were calculated, since cooling is insignificant at altitudes over 600 m, let alone altitudes over 800 m where cooling tends to be eliminated, as proved by the nearly zero values of the “real” cooling degree-days.

After the HDDs calculation, the variation of energy demand within an area can be assessed. Specifically, given the air temperatures and the HDD values of all meteorological stations within the country, the variation of heating, cooling and total energy needs of the same building located at different altitudes (keeping constant technical characteristics) can be calculated, according to Equations 7, 8 and 9. Moreover, Equation 6 can give the ratio of heating to cooling needs. An indicative example of the practical use of the methodology suggested is displayed in Table 2, where a random selection of meteorological stations including low and high altitudes was made for Austria, Switzerland, Greece and north Italy.

Table 2. Allocation of energy demand with altitude for a building located in Austria, Switzerland, Greece and north Italy [1,2]

Country	**Meteorol. station**	**Altit. (m)**	**Annual HDD (°C*days)**	**Percent. increase of heat. needs (%)**	**Annual CDD (°C*days)**	**Percent. decrease of cool. needs (%)**	**Percent. variat. of total needs (%)**	**Ratio of heating / cooling needs (%)**	
Austria	Linz-Stadt	263	2357		181			92,9	7,1
	Flattach-Kleindorfl	735	2920	+23,9%	105	-42,2%	+19,2%	96,5	3,5
	Badgastein	1092	3247	+37,8%	20	-89,0%	+28,7%	99,4	0,6
Switzerl.	Lugano	273	1503		410			78,6	21,4
	Chur	556	2101	+39,8%	184	-55,2%	+19,4%	92,0	8,0
	Davos	1594	3591	+138,9%	20	-95,1%	+88,8%	99,4	0,6
North Italy	Bozen/ Bolzano	272	2236		260			89,6	10,4
	Brixen/ Bressan.	569	2659	+18,9%	134	-48,4%	+11,9%	95,2	4,8
	Predazzo	1020	3233	+44,6%	20	-92,3%	+30,4%	99,4	0,6

1 Cooling is meaningless over 900 m for all cases. The value of 20 CDD at high altitudes has been set as a default value in order to enable calculations.

2 The percentage variation of energy needs at each level has been calculated in respect with the first level (the meteorological station with the lowest altitude).

Greece	Lamia	143	1192		481			71,2	28,8
	Konitsa	542	1543	+29,4%	249	-48,2%	+7,1%	86,1	13,9
	Karpenisi	980	2074	+74,0%	20	-95,8%	+25,1%	99,0	1,0

As seen in Table 2, heating needs gradually increase versus altitude while cooling needs decrease. Yet, despite the decrease of cooling demand, total energy needs always increase with altitude for all cases. As an example, for the case of Switzerland, heating needs at 1594 m altitude are 2.4 times higher compared to those at 273 m while cooling needs are 20.5 times lower. Besides, total energy needs (heating and cooling) are still significantly higher, by 5.3 times. Presenting the results for another case study, such as Greece, it is indicated that heating needs at 980 m altitude are 1.7 times higher compared to those at 143 m (close to sea-level), cooling needs are 24.1 times lower and total energy needs are 1.3 times higher. The results show that a dwelling at a high altitude region has to spend much more money in order to achieve an adequate level of energy comfort, in all cases examined.

Moreover, the crucial role of heating energy demand is revealed. It appears that the great majority of energy needs are heating needs, not only at high altitudes but also at lower ones, with the share of heating demand versus cooling demand exceeding 70 percent at the lowest altitudes, let alone the highest ones where the share of heating needs reaches up to 99 percent.

In this way, the energy identity of an area can be determined. If the technical characteristics of buildings are also included, then an even more precise calculation of heating and cooling energy demand of buildings can be achieved, through the Equations (4) and (5).

4 Conclusions

Mountainous areas, fully enriched with renewable energy potential, and many times far away from national energy grids, seem to be ideal for the implementation of renewable energy technologies. Main objectives of the paper were, firstly, to overcome the obstacle of sparse meteorological stations at high altitudes and, secondly, to develop a method determining the energy demand of buildings in a simple way.

Regarding the four case studies, namely Austria, Switzerland, Greece and north Italy, four lapse rate values were estimated, at a country level. It appears that the lapse rates, indeed, differ from the common used value of 6.5°C/km, ranging from 4.9°C/km to 6.0°C/km. In this way, the air temperatures, as well as the heating degree-days of high altitude areas were calculated, using the temperature data of their nearest station. The differences arising in the calculated HDDs were found to be quite small when compared to the “real” ones, with a mean annual deviation of 7 percent, thus providing adequately reliable estimations.

Since verified that HDDs at high altitudes can be estimated with high accuracy, the energy profile of the four mountainous regions was formed. As an example, examining the energy profile along an altitudinal range of 800 m for the case of Austria, it was found that heating energy needs at the highest altitude are 1.4 times higher compared to the lowest one, cooling energy needs are 9.1 times lower and the sum of energy needs for heating and cooling are also higher, by 1.3 times. Moreover, it was proved that, in all cases, thermal energy demand is the core of energy demand, even at low altitudes.

Overall, the method suggested, based on thorough statistical analysis of long term meteorological data, provides an easy and reliable way of determining the energy needs of a mountainous region, helping in developing a tailor cut energy plan, using the abundant renewable energy sources found in mountains.

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