

## MODELLING OF ENERGY DEMAND FOR HEATING BUILDINGS, HEATING TAP WATER AND COOKING IN RURAL HOUSEHOLDS

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**Summary.** The study presents a model of demand for energy in the housing sector, suitable for use by local self-governments for drawing up heat supply plans. The model uses indicators, which are typical for the rural areas in Southern Poland, based on the statistics available from communes. With the use of the model, it is possible to establish the energy demand for heating residential buildings, heating water and cooking, with the error not exceeding 3%.

**Key words:** energy distribution planning, energy consumption for heating buildings, heating tap water and cooking

### INTRODUCTION

Pursuant to the Energy Law [Dz. U. Nr 54, 1997] and to the Territorial Self-Government Act [Dz. U. Nr 13, 1996], the local self-governments are obliged to develop plan assumptions and the plans of heat, electric energy and gas fuel supply for their area. Identifying the heat demand in individual regions is of vital importance for energy planning [Robakiewicz 1988]. Establishing the actual demand is especially difficult in rural areas, where single-family houses prevail, in which the heat demand of the residents is mainly satisfied by individual sources of heat.

The main consumer of heat energy in rural areas is the housing sector, as it uses above 80% of the total energy supply for heating tap water and cooking [Robakiewicz 1998, Mróz 1999]. Assessing the energy demand for grouped structures in that sector can be achieved by means of energetic audits [Augusiak and Bućko 2000], which – at a large number of households – is costly, time consuming and difficult. For that reason, the local self-governments often utilize unit energy consumption indices for drawing up the plans. The literature available in that field is of little use for planning, as usually theoretical demand is presented, instead of the actual consumption of heat energy [Trojanowska and Szul 2003].

The study is aimed at developing models reproducing the energy consumed in rural communes for heating houses, tap water and for cooking, in a form allowing their practical use by territorial self-governments for planning energy supplies.

## MATERIAL AND METHODS

In order to achieve the objective set, surveys were made in 400 households chosen at random, representing the rural areas of Małopolskie Voivodship. The number of surveyed households was established, to ensure an assessment of final energy consumption, with the average error of around 5%.

In the surveys (aside from the data regarding fuel demand during the heating season) of the living area and height of the rooms, the details were gathered concerning, among others, the heated area, methods of heating buildings and tap water, cooking, type and year of manufacture of central heating boilers and thermal insulation of the buildings.

The results of the surveys were utilized for developing models which reproduce the energy consumed for heating buildings, hot water and cooking, in which the energy demand is explained by means of variables available from statistical data of the communes. The following figures have been considered: the number of residents, the number of households and their structure with regard to the number of residents, the number of residential buildings and the year of construction, the cubage of the residential buildings.

## RESULTS

### Energy demand for heating residential buildings

The seasonal annual consumption of energy carriers for heating buildings is presented in the dependency [Mizielińska 1997]:

$$B_o = \frac{0,001 \cdot q \cdot V \cdot \Delta t \cdot \Phi_m \cdot 24 \cdot z}{\eta_p \cdot \eta_k \cdot W_u} \quad (1)$$

where:

$B_o$  – seasonal fuel consumption for heating buildings, t or m<sup>3</sup>,

$q$  – unit heat energy demand index W/m<sup>3</sup>•K,

$V$  – building cubage, m<sup>3</sup>,

$\Delta t$  – indoor and outdoor temperature difference, K,

$\Phi_m$  – peak power usage degree,

$z$  – number of heating season days per year,

$W_u$  – fuel caloric value, kW•h/t or kW•h/m<sup>3</sup>,

$\eta_p$  – central heating system efficiency,

$\eta_k$  – boiler efficiency.

The unit heat energy demand index is a function of multiple parameters, having immediate effect on peak and momentary values of the power, required to cover the heat loss resulting from heat transfer through various structural partitions, and the heat loss attributable to heat exchange (ventilation and air conditioning) in the rooms. The peak demand for heat energy depends not only on the technical condition of a building, but also on the requirements and recommendations set out in various standards and technical specifications related to the issue in question.

The indicative unit energy demand for heating a building, having no technical documentation available, can be obtained from the formula [Kamler 1976, Krygier 2001]:

$$q = w \cdot \frac{1.6}{\sqrt[6]{V}} \quad (2)$$

where:

$w$  – corrective factor, other items as per formula 1.

It corresponds to the heat loss occurring when heating 1 m<sup>3</sup> of a building, referenced to the unit outdoor/indoor temperature difference. Based on statistical studies carried out in the existing structures, it was found that the corrective factor of the unit heat power demand in buildings above 1000 m<sup>3</sup> is 1 [Kamler 1976]. In order to obtain the factor for structures of lower cubage, the survey was carried out in 174 residential buildings, for which abridged energetic audits were made, according to PN-B-02025. After analysing the results, it became evident that the factor value correlates well with the years in which the buildings were built. Mean values of the corrective factor, depending on the building age are given in the Table 1.

Table 1. Mean values of the corrective factor, depending on the building age.

Year of construction	$w$ – corrective coefficient
before 1950	1.92
1950–1960	1.87
1961–1970	1.76
1971–1980	1.58
1981–1990	1.34
since 1990 (with upgraded thermal insulation)	1.00

Source: own calculations

As the present study is narrowed to only determine the final energy consumption for heating structures located within rural areas of southern Poland, certain items of the formula 1 have been assumed as constant. They are as follows:  $\Delta t = 40$  K [PN-82-B-0240 for the III climatic zone] and  $z = 222$  [PN-B-0202]. In addition, in the paper the following was assumed:  $\eta_p = 0.95$  [Duńsko-polski program 1998],  $\Phi_m = 0.32$  for heating systems equipped with gas-fired boilers and heat pumps and  $\Phi_m = 0.4$  for heating systems fired with solid fuel [Bąkowski 1996, Mizielińska 1997, Grochowski 2004].

After inclusion of those assumptions and conversion to tpu, the energy demand for heating residential building can be obtained from the formula modified as follows:

$$B_{ogd} = \frac{c \cdot \sqrt[6]{V^5} \cdot w}{\eta_k} \quad (3)$$

Whereas:  $c = 0.014$  for residential buildings heated with gas or using heat pumps and  $c = 0.0175$  for residential buildings heated with solid fuels. Besides the following was assumed:  $\eta_k = 0.7$  for boilers fired with solid fuel, currently in use,  $\eta_k = 0.8$  for mod-

ern boilers fired with solid fuel (manufacturers' data),  $\eta_k = 0.85$  for boilers fired with gas,  $\eta_k = 3.3$  for heat pumps.

### Energy demand for hot tap water

Annual consumption of energy carriers for heating tap water is obtained from the formula:

$$B_{cwu} = \frac{Q_{cwu} \cdot 365}{\eta_{cwu} \cdot W_u} \quad (4)$$

where:

$B_{cwu}$  – annual consumption of energy carriers for heating tap water, t or m<sup>3</sup>,  
 $Q_{cwu}$  – daily heat demand for preparing hot water, kW·h,  
 $\eta_{cwu}$  – efficiency of the equipment for heating water,  
 $W_u$  – calorific value of the fuel, kW·h/t or kW·h/m<sup>3</sup>.

The daily heat demand for heating water can be obtained from the dependency [Mańkowski 1981, Bąkowski 1996]:

$$Q_{cwu} = n_m \cdot G_{sr} \cdot c_w \cdot (t_{cw} - t_{wz}) \cdot 3600^{-1} \quad (5)$$

where:

$Q_{cwu}$  – daily heat demand for preparing hot water, kW·h,  
 $n_m$  – number of residents, Mk,  
 $G_{sr}$  – average daily consumption of hot water per one resident, kg/Mk,  
 $c_w$  – water specific heat, kJ/kg·K,  
 $t_{cw}$  – calculated temperature of hot water, K,  
 $t_{wz}$  – cold water mean temperature per annum, K.

The literature on the subject of the housing sector provides various values of daily demand for heated water per one resident: 20–40 [Bąkowski 2000], 40–60 [Chochowski i in. 1996], 60–80 kg/Mk [Mańkowski 1981]. In order to establish such index for rural households, the consumption of hot water was surveyed, and the details on the actual consumption for household needs were used [Bergel and Satora 2003, Ślizowski and Bugajski 2003]. The average cold water consumption in rural households ranges around 60 kg/Mk. Based on the author's studies, the hot water was assumed to be 50% of the total water used by a statistical resident of rural regions in 24 hours.

As in the rural communes surveyed, the households are supplied with water from abyssal wells, it has been assumed that the average cold water temperature  $t_{wz}$  is 12.5°C, and the hot water temperature  $t_{cw}$  is 45°C [Mańkowski 1981].

After introducing the above values to the formula 8 and converting them to tpu, the annual consumption of final energy for heating water is as follows:

$$B_{cwu} = \frac{0.051 \cdot n_m}{\eta_{cwu}} \quad (6)$$

The following figures have been assumed as the equipment efficiency [Mizielińska 1997, Grochowski 2004]:  $\eta_{cwu} = 0.8$  for gas fired equipment,  $\eta_{cwu} = 0.9$  for electric equipment,  $\eta_{cwu} = 0.5$  for equipment fired with solid -fuel.

### Energy demand for cooking

The subject-related literature provides various figures of annual consumption of energy for cooking per an average household. The figures differ significantly and range between 1095 kW·h and 1888 kW·h [Grochowski 2004].

Due to the fact, that the energy consumption for cooking depends on the number of residents in a household, the author's own studies were carried out in rural households, in order to establish the annual energy consumption for cooking (Table 2).

Table 2. Annual energy consumption for cooking in households

Households	Q <sub>pos</sub> kW·h/household
One resident	690
Two residents	820
Three residents	950
Four residents	1080
Five residents	1210
Six residents	1340

Source: own study

The annual final energy consumption for cooking converted to tpu is presented by the formula:

$$B_{pos} = \frac{Q_{pos}}{8139 \cdot \eta_{pos}} \quad (7)$$

where:

$Q_{pos}$  –annual energy consumption for cooking in a household, kW·h,

$\eta_{pos}$  – cooker efficiency.

For calculations of the annual final energy consumption for cooking, the following has been considered [Grochowski 2004]:  $\eta_{pos} = 0.7$  for electric cookers,  $\eta_{pos} = 0.6$  for gas cookers,  $\eta_{pos} = 0.5$  for coal-fired cookers.

### VERIFICATION OF MODELS

In order to verify the models, their accuracy and sensitivity is assessed in the study. The assessment of models accuracy has been carried out based on the value of relative percent error, obtained from the dependency:

$$\psi = \frac{B_{rz} - B_m}{B_m} \cdot 100 \quad (8)$$

where:

$\psi$  – relative percent error, %,

$B_{rz}$  – actual final energy consumption, tpu,

$B_m$  – final energy consumption obtained from the model, tpu.

As a result of a comparison of the values calculated with the use of models with the empirical values obtained from the study, a relatively good consistency was achieved. The mean values of the relative percent errors did not exceed 3%. As the models allow also to calculate the consumption of individual energy carriers, additional calculations were made for coal, natural gas and timber, which resulted in a similar accuracy.

Another verification criterion of the model is the sensitivity assessment. The assessment involves a series of several dozen model solutions for varying parameters. The choice of model parameters was, first of all, governed by the necessity to include possibly the most critical parameters, in terms of their effect on the results of calculations. The studies were carried out for several scenarios, taking into consideration, among others, the replacement of coal-fired boilers with others, modernisation of thermal insulation of residential buildings and the change in structure of households, in terms of the number of residents sharing one household.

As a result of simulations performed for individual scenarios, the model responses were forming an apparently monotonous line. On these grounds it was possible to state that the model had been constructed correctly.

## CONCLUSIONS

1. The models of energy demand for heating residential buildings, heating water and cooking, explained in the study, are suitable for planning heat supply in the rural communes, as they are based on the data available from the communes' statistics and allow to establish energy demand for those purposes with an error which does not exceed 3%.

2. The study of hot water consumption in rural households, carried out in order to develop the model of energy demand for heating water, revealed that a statistical resident of those households uses on average 30 dcm<sup>3</sup> of hot water daily, which represents approx. 50% of the total water consumption for household needs.

3. The knowledge of unit consumption of energy for cooking is necessary to establish the demand for the related final demand. Based on the studies carried out, it has been found that the average annual consumption of heat energy for cooking in households, depending on the number of residents, falls within the range of 690–1340 kW·h.

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