Residential building retrofit effectiveness analysis based on heat and water use data

Denis Dogadin
Foundation for Enterprise Restructuring and Financial Institution Development
3/5 Smolensky blvd, P.O. Box 4, Moscow, 119121, Russia
ddogadin@fer.ru

Oleg Komarov & Boris Nekrasov
Foundation for Enterprise Restructuring and Financial Institution Development
3/5 Smolensky blvd, P.O. Box 4, Moscow, 119121, Russia
okomarov@fer.ru, bnekrasov@fer.ru

Keywords

building performance indicators, retrofits, heat saving, water saving, thermal comfort, retrofit efficiency

Abstract

This paper presents the results of an analysis of experimental data on heat and water use, acquired prior to and after residential multifamily building retrofits in six Russian cities under the International Bank for Reconstruction and Development Enterprise "Housing Divestiture Project".

The paper reports:

- specific characteristics for heat and water use obtained as a result of unique measurement program in about 100 buildings of various types, connected to district heating systems of 6 different types and retrofitted using over 40 technologies. The source data used were hourly and daily instrumental readings collected over periods of 2-4 years;
- descriptions of various approaches to modeling heat and water supply conditions for the purpose of predicting heat and water use and taking into consideration the influencing factors – outside temperature, operating mode of the district heating system, and the air temperature in apartments;
- data on realized heat and water savings (up to 30%);
- analysis of variations in the thermal comfort in retrofitted buildings;
- estimation of untapped energy-saving potential.

The results obtained provide a basis for optimal selection of building retrofit technologies using AuditHelp spreadsheets developed by Foundation for Enterprise Restructuring and Financial Institutions Development, which will ensure obtaining maximum heat saving, of which the overall potential in the housing and utility sector of Russia is estimated at 120 – 135 million Gcal (500 – 560 million GJ) per year.

Introduction

The Enterprise Housing Divestiture Project is managed by the Russian Government, through the Non-Commercial Foundation for Enterprise Restructuring and Financial Institutions Development (FER). The project has been running during the period from 1996 to 2003 and is partially financed by a $ 134 million loan from the International Bank for Reconstruction and Development.

The primary objective of this Project is to accelerate and make sustainable the divestiture of enterprise housing stock in eight participating cities and its transfer to municipalities[1]. The Project supports reforms that push the ownership, financing, and management of the housing stock into the private sector, which is an integral aspect of the economic transition occurring in Russia. Secondary objectives of the Project include a wider range of reforms such as housing privatization, cost recovery of housing maintenance and utility fees from tenants, targeted housing allowances, competitive

1. In Soviet era enterprises (factories, industrial plants etc) provided housing, schools, health care, and recreational facilities for the workers. Housing services were essentially free. As part of the process of enterprise privatization in the early nineties, ownership of the enterprise housing stock is being divested to the munucupal governments.

bidding for maintenance of housing, and improved energy efficiency in divested housing.

The participating cities are Petrozavodsk (Republic of Karelia), Volkhov (Leningradskaya oblast), Cherepovets (Vologodskaya oblast), Izhevsk (Republic of Udmurtia), Vladimir, Ryazan, and Orenburg.

In order to improve energy efficiency, it is planned to install 4 003 metering units for heat, water, electricity and gas, to retrofit 1 563 multifamily residential buildings, to construct or modernize 14 boiler houses, to reconstruct 78 central heat substations and at least 154.7 km of pipelines in the district heat and water supply systems.

Retrofitting of multi-apartment residential buildings for the purpose of energy and water saving includes:

- modernization of individual heat substations (IHS) by installing state-of-the-art equipment (heat exchangers, pumps, controllers, etc.); replacement and repair of pipes; and flow balancing of space heating (SH) and domestic hot water (DHW) supply systems. Taken together, these improvements permit automatic control of heat use depending on the outside temperature and provide more uniform and sustained supply of all apartments with heat and domestic hot water;
- works on reducing the heat losses, including thermal insulation of outer walls (facades, ends and arches), heat insulation and waterproofing of roofs and technical attics, placing heat insulation on the floors of ground floor rooms, repairing windows and doors in apartments and stairwells, caulking of panel joints, insulating the pipelines in the space heating and water supply systems;
- measures towards economic use of water and improvement of its delivery into apartments, including installation of booster pumps, replacement of risers, fixing of toilets, installation of low-flow faucets and showerheads, and installation of per apartment water metering devices.

To select optimal packages of retrofit measures and to evaluate the Project effectiveness, a comprehensive program of building and upstream site audits, operational data collection and analysis has been implemented since 1996. The AuditHelp software was developed in 1997 to assist the process of building auditing and to automate routine calculations of building heat balance and preliminary selection of building retrofit packages. AuditHelp has been developed further to include detailed heat balance models, input of measured operation parameters, compilation of databases for equipment and labor cost, energy and water tariffs, theoretical and factual energy and water savings, etc. A review of the building operation parameters measurement program, data treatment methods and results obtained on energy and water savings is presented below.

A Review of Measurement Program

DESCRIPTION OF MEASURING SYSTEMS AND COLLECTED SOURCE DATA

The metering equipment used for data collection was implemented in 2 stages. The 1st stage covers 40 buildings and was started in 1996 (EHDP, Battelle, 1998).

Electric Meters. The electricity use being measured was that by apartments and not areas such as stairwells, other common spaces or elevators.

Heat Meters. Metered heat data were collected from the supply and return leg of the heating system in each building using well-type temperature and flow sensors installed where the supply and return pipes enter the multifamily building from the district heating (DH) system.

Hot Water Meters. Domestic Hot Water (DHW) flow and temperature data were collected on both the supply and return legs at the critical entrances and exits inside the multifamily building when recirculating hot water systems were used.

Cold Water Meters. Cold water (CW) flow data were collected on the supply leg of the cold water system. Strap-on thermocouples on the cold water pipes were also used to measure temperatures of those flows and enable calculation of the heat extracted from the buildings and the heat required to produce DHW.

Gas Meters. Our intention was to use gas meters to measure natural gas consumption in the buildings. Our monitoring in the Ryazan demonstration buildings showed clearly the significant addition of gas heat from stoves to heat apartments during unusually cold periods. However, for a number of reasons, gas meter installations were not entirely successful and thus metered gas consumption data were collected only in a limited number of cases.

Meteorological Stations. Meteorological stations on the top of one building in each city also measured weather conditions. The information collected includes wind speed and direction, barometric pressure, total horizontal solar radiation, relative humidity, and temperature.

Additional Thermocouples. Additional measured temperature data were collected from thermocouples in basements and stairwells and on the main sewer collection point serving at least one representative section in each building. These temperature data were needed to measure the envelope heat balance components associated with service & waste water pipe losses. Lastly, data on water temperature in the space heating system were collected in each building.

Data from each of the above-named instruments were transmitted to a logger for hourly recording.

Indoor Temperature Sensors and Loggers. Within each building, numerous room temperature sensors and loggers were used to collect the hourly indoor temperatures in apartments. Locations for placement included apartments from top, middle, and bottom floors.

The 2nd stage covered additional 119 buildings and started in 1999.

The program of additional measurements was implemented, intended to broaden the measurement program. Supplementary efforts toward collection of data and carrying out measurements were necessary to acquire sufficient statistical data for an objective evaluation of the existing situation and, consequently, for obtaining valid data on energy and water savings in six cities participating in the Project. Flow meters, heat meters and data loggers had been installed on buildings so as to obtain such data separately from each of the building engineering systems (space heating, CW and DHW supply). In total, over 220 units of measuring equipment had been installed or upgraded on 159 buildings.

Table 1. Characteristics of buildings under survey

City	Number of buildings	Year of construction				Number of floors			Wall material			Average number of tenants per building	Average floor square per building, m^2
		Before 1972	1972-1981	1982-1991	1992-1995	5	9	>9	panel	brick	other		
Cherepovets	20	0	11	9	0	10	6	4	11	7	2	188	6 515
Orenburg	16	0	6	7	3	4	11	1	11	3	2	281	6 977
Ryazan	20	0	3	15	2	3	13	4	14	1	5	324	8 167
Vladimir	18	3	1	13	1	5	11	2	12	5	1	235	6 311
Volkhov	6	4	0	2	0	5	1	0	2	4	0	123	3 536
Petrozavodsk	12	2	2	8	0	1	4	7	8	4	0	229	6 221
Total	**92**	**9**	**23**	**54**	**6**	**28**	**46**	**18**	**58**	**24**	**10**	**244**	**6 464**
	100%	**10%**	**25%**	**59%**	**7%**	**30%**	**50%**	**20%**	**63%**	**26%**	**11%**		

Data acquisition is performed at hourly or daily intervals on these buildings (about 40 000 of various parameter values were recorded daily).

Indoor air temperature was measured by between 7 and 15 room temperature loggers (RTL) per each of 159 buildings. In all, about 1 600 RTLs have been installed.

There are three typical Russian heating schemes in the selected buildings: 2-pipe (combining the heating water and domestic hot water into a single loop), 3-pipe (using a building-level heat exchanger to heat domestic water), and 4-pipe (using a large heat exchanger at the central heat substation to provide domestic water heating for several buildings). The configuration of heat and water metering units to be installed in each building was selected accordingly.

DESCRIPTION OF BUILDINGS UNDER SURVEY

This paper presents results obtained from 92 buildings[2] of various types in six cities situated in the European part of Russia. The characteristics of the buildings are summarized in Table 1.

Description of approaches to modeling heat and water supply conditions and savings estimation

Construction of a model for heat use by a building before and after retrofit and determination of heat flow in the conditions of the calculation period

The heating systems in the buildings comprise the SH system and the DHW system. Heat use in the SH system is seasonal and its output depends on the outside air temperature. In the DHW system, heat is used all year round in typical daily, weekly and annual cycles. These principal distinctions between the operating conditions of the SH system and the DHW system have provided the reason for developing separate heat use models for each system.

The difference in the heat supply schemes and, accordingly, the diagrams for installation of measuring instruments called for application of several models. The models obtained were used to fill in data missed in the periods prior to and following the retrofits, and to determine the heat flow in a building over the calculation period taken to mean the one-year period between August 2001 and August 2002.

Building of the models was done on the basis of daily averages.

Determination of effects derived from implemented retrofits

The effects derived from implemented retrofits were defined by comparing the flows of heat and water in different building facilities (SH, DHW, and CW systems) prior to and following retrofits over a calculation period.

Calculation of specific indicators of heat and water use by buildings

In the Russian system of standards there are two fundamentally different approaches to rating the heat use by residential buildings:

- element-by-element standards for thermal insulation provided by building enclosures (traditional approach),
- standardization of the thermal insulation level for the building as a whole as a single energy system taking into consideration the effectiveness of space heating systems. This method was proposed in 1994 by the Science and Research Institution for Construction Physics (NIISF, Moscow), the Centre for Energy Efficiency (CENEf, Moscow) and was used in a number of recently approved territorial construction standards. This approach rests on the value of design specific flow of thermal energy to heat buildings [$Wh/m^2.K.day$] and on the design factor of energy effectiveness in the heat supply system.

Considering the new trends emerging in the field of standards for heat-protection properties of buildings, under the present work specific indicators of heat use by space heating systems of the buildings under survey were determined, including the above-mentioned specific flow of thermal energy for space heating of buildings.

Calculations were done in the MS Excel. For evaluation of statistical magnitude and significance of the dependencies obtained, specialized software "Statistics" developed by StatSoft Inc. (USA) was employed. A description of approaches applied at every stage of analysis is given below.

DESCRIPTION OF APPROACH TO MODELING HEAT USE IN A SPACE HEATING SYSTEM

The space heating system under any operating conditions must provide a constant standard air temperature in an apartment by compensating the heat loss of the building,

2. At the time of writing, this is the number of buildings for which it has been possible to gather reliable data before and after retrofits.

which are practically in a linear dependence from the outside air temperature, i.e. heat use by a building through the space heating system must also be a linear function of a single variable – outside air temperature.

However, the district heating systems in Russia have a number of peculiar features in operation, among which the following may be identified:

1. The only kind of regulation in most buildings connected to a DHS is central control, in particular, its most common type – qualitative central control of combined SH and DHW load, whereby the heating medium temperature varies under a constant flow. A drawback of this control is maintaining the heating medium temperature at or above 70˚C, which is due to the necessity of delivering the heating medium to the consumer at a temperature sufficient for heating the DHW to a design level (55-65˚C). This peculiarity leads to overheating emerging in a period of high outside air temperature.
2. On account of ageing of heat-generating equipment and heat distribution pipelines[3] heat supply companies often impose restrictions on the maximum temperature of the heating medium by 20-40˚C below the design temperature adopted in designing the heat supply and heat use systems. This peculiarity leads to underheating in the coldest period of the year.
3. Failure to observe the design temperature curve for the heating medium by the heat supply companies due to conflicting situations with fuel supply companies, caused mainly by non-payments for gas due to underfinancing of the heat supply companies themselves.
4. Connection of the majority of buildings to the heat supply system is by uncontrolled ejector mixing pumps (hydraulic elevators), the purpose of which is to reduce the water temperature from design values adopted in the district heating system (design temperature in the supply line being 150 (or 130) ˚C, in the return line - 70˚C) down to design values in the space heating system (design temperature being 105 (or 90) ˚C in the supply line, in the return line - 70˚C). As long as the mixing factor of the hydraulic elevators does not change (Sokolov, 1999), the flow and temperature of the heating medium inside buildings varies practically in proportion with variations of flow and temperature of the heating water.

This makes it necessary to use the dependence of heat flow in the space heating system on the heat supply system parameters. Description of several proposed approaches is given below.

Where water flow is closely controlled

Heat use by the space heating system with qualitative control in buildings, whereby fluctuations of the heating water flow during a heating season are within the range of 5-10%, may be described by the simplest regression model:

$$Qht = C + C_1 * Tdh, \qquad (1)$$

where

Qht – heat use by the building space heating system;

C and C_1 – factors;

Tdh – heating water temperature at the inlet to building.

Where water flow is reasonably controlled

In practice, however, district heating systems are often operated at significantly higher flow variations, which during the heating season may be as high as 30-40%. In this case, it is advisable to use a more precise dependence:

$$Qht = C + C_1 * Tdh + C_2 * Vdh, \qquad (2)$$

where

C_2 – factor;

Vdh – heating water flow per building.

An advantage of employing these models lies in their high statistical magnitude[4] and significance, which makes it possible, based on a minimum amount of source data obtained over a short period, to estimate the value of annual heat use.

A drawback is their limited applicability. If there is a significant change of heating water flow in centralized control of the thermal load, none of the models may be applied to predict the heat use by a building prior to retrofit under the conditions of a calculation period[5]. Where conditions allow, application of these models permits:

- the restoration omitted data on the use of heat in space heating for buildings over a period prior to and after the retrofit;
- in some cases, the prediction of heat use by a building prior to the retrofit under the set of conditions of a calculation period.

Where heating water flow varies widely

In those cases when the application of the above-given models is not legitimate, a non-linear dependence of heat flow on the outside air temperature was applied to predict heat use in the space heating system under the conditions of a calculation period (EHDP, TAG-2, 2001). This model was founded on the classical relationship between heat consumption and difference of inside and outside temperatures:

$$Qht = K * (Tap - Tos), \qquad (3)$$

where

K – function describing heat-protection properties of a building and mode of operation of heat supply system;

Tap – temperature of inside air;

Tos – temperature of outside air.

3. According to official data, the average deterioration of heat generating equipment and pipelines across the country is about 35% and 60% respectively (Minenergo RF, 2002).
4. Statistical magnitude indicates the degree of correspondence - i.e. strength of relationship - between two variables. Examples include means, variances, correlation coefficients, and others.
5. When using the second model, the flow data in the calculation post-retrofit period will no longer reflect the operating conditions of the district heating system since they change as a result of the new IHS equipment in operation.

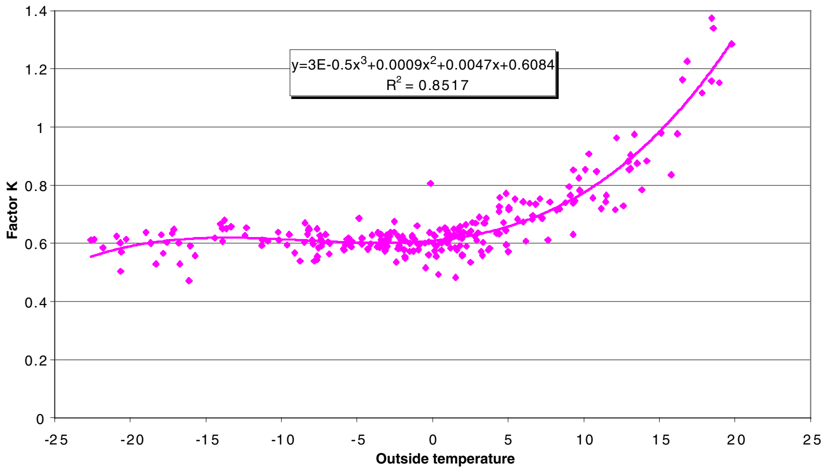

Figure 1. *Factor K versus outside air temperature.*

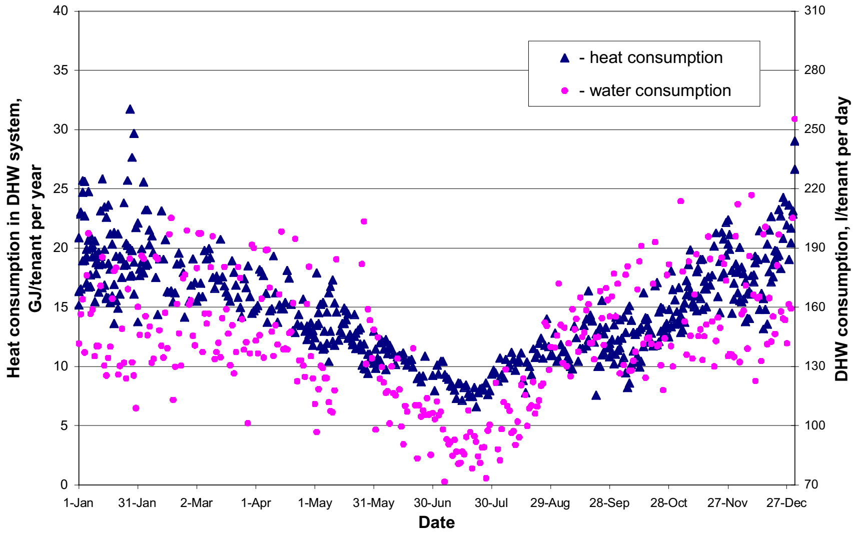

Figure 2. *Variation of heat and water consumption in DHW system during the year.*

Assuming that during the calculation period the heat loss properties of a building do not change and the mode of operation of heat supply system maintains the temperature in apartments at a normal level, the value *K* is constant. If there is poor control of heat delivery into the space heating system and deviation of the air temperature in apartments from the values of comfort, the value *K* changes. For example, when indoor temperatures are too low, the tenants add heat to apartments using gas stoves and electric heaters and *K* in this case diminishes. When they are too high, the tenants open windows and thus increase the infiltration component of heat loss, which causes *K* to increase. Figure 1 shows an example chart for *K* versus outside air temperature.

DESCRIPTION OF APPROACH TO MODELING HEAT AND WATER USE IN THE DHW SYSTEM

Figure 2 shows an annual profile for heat and water consumption in the building DHW system, built from daily data acquired during a period of one-and-a-half years.

As may be seen from this chart, during the year one can observe a considerable change in the heat and water use. This is mainly due to a variation of the following parameters: DHW temperature; CW temperature (affecting the heat flow only) and occupancy, which depends on the season and the day of the week.

A typical feature of operating the DHW system of buildings is a significant variation of the DHW temperature. This situation is due to the following reasons:

1. delivery to consumer of hot water having a temperature below the specified level (55-65°C) because of failure of the heat supply company to follow the temperature curve;
2. lack of automatic control over the DHW temperature - temperature controllers in many Russian buildings either have not been installed, or are in a state of disrepair[6]. In this situation, the hot water temperature practically coincides with the heating water temperature.

The annual use of heat and water in the DHW system is strongly affected by the type of water draw-off fittings and their condition, the availability of a recirculation line preventing the morning runoff of water that has cooled off during the night, and the motivation of tenants in favour of economic use of water.

To estimate the effect on the DHW system, an approach has been adopted under which the value of heat and water saving in the DHW system is found by way of a direct comparison of annual heat and water consumption before and after retrofit. This approach makes use of a number of assumptions, including that there is no year-to-year change to the temperature of cold and heating water, occupancy fluctuation, and the ratio of consumption on weekdays to consumption on days-off.

The problem connected with filling in missing data to determine the annual flows of heat and water prior to and following retrofit was resolved on the basis of empirical coefficients describing the variation of water and heat flows during the year; in other words, use was made of the annual heat/water flow profile similar to the one shown in Figure 2. When employing this approach it is essential that specific peculiarities of the DHW system operation in buildings are taken into consideration, since the degree of impact by factors determining a variation of heat/water flows for DHW within a year may differ significantly. For example, if in one case cold artesian water having a practically constant temperature of 7-10°C during the whole year is used for DHW preparation, and in another case it is the river water, the temperature of which is varying between 2 and 23°C, then the difference between the water flows in summer and in winter will be considerably less in the first case, and that means that the annual profile will change too. Another example refers to peculiarities of controlling DHW temperature: in a system with automatic control it is maintained constant throughout the year, whereas in a system without a DHW regulator it varies by 40-60°C.

Processing and analysis of data on water flows in the CW system were done in a similar manner.

DESCRIPTION OF APPROACHES TO DETERMINING THE EFFECT DERIVED FROM RETROFITS

The following components of the effect are considered:

- Money savings owing to establishment of commercial metering for heat and water;
- Direct savings of heat and water;
- Indirect savings (when calculating the effect in SH system); and
- Estimation of untapped energy-saving potential (when calculating the effect in SH system).

The base level, in relation to which all the components of the effect were determined, was taken to be the official standard level of heat and water supply.

Money savings owing to establishment of commercial metering for heat and water

The share of residential buildings equipped with commercial heat and water meters is low. In this situation, in most cases settlement of accounts with the heat supplying organization is accomplished on the basis of design heating load and standard water consumption approved by municipal authorities. For calculation of eventual money savings from the introduction of commercial metering, the difference was found between the standard consumption of heat (water) and the measured consumption of heat (water) prior to retrofit over the calculation period[7]:

$$dQ(V)m = Q(V)^n - Q(V)', \quad (4)$$

where

dQ(V)m – difference between standard and measured heat (water) consumption prior to retrofit over the calculation period;

$Q(V)^n$ – annual standard consumption of heat (water);

Q(V)' – consumption of heat (water) at a building over the design period prior to retrofit.

Direct savings of heat and water

Direct savings were found as the difference in consumption of heat (water) prior to and following retrofit under the calculation period conditions:

$$dQ(V)d = Q(V)' – Q(V)'', \quad (5)$$

where

dQ(V)d – direct heat (water) savings,

Q(V)" – consumption of heat (water) at a building over the calculation period following retrofit.

Indirect savings of heat

This component of the effect derived in the space heating system reflects the level of comfort improvement in a building under equal external conditions (outside air temperature and heating network operation parameters). For quantitative assessment of indirect savings, we used the so-called thermal equivalent of comfort change. This thermal equivalent of the comfort change corresponds to an additional quantity of heat that would have been needed in a non-retrofitted building so as to provide the conditions of comfort similar to those provided in a retrofitted building over the calculation period.

This component of the effect results from retrofits that improved the thermal insulating properties of the building envelope. Assessment of indirect savings was done based on the actual thermal loads of the building before and after retrofit by formula:

$$dQi = (Qhd' – Qhd'')*(Tap^n – Tos^h)/(Tap^n – Tos^d)*Z, \quad (6)$$

where

dQi – indirect savings;

Qhd' – actual heat demand of the building before retrofit;

Qhd" – actual heat demand of the building after retrofit;

6. Before retrofitting, DHW temperature controllers were missing in practically every building.
7. Evaluation of effects in terms of money goes beyond the bounds of this paper, therefore calculation results are cited as thermal equivalent only.

Tap^n – standard air temperature in apartments;
Tos^h – average air temperature over the heating season;
Tos^d – design outside air temperature;
Z – duration of the heating season.

Value dQi shows how much heat may be saved within a heating season in a building with ideal control of the heat demand and maintenance of the standard temperature in apartments both before and after its retrofit. In practice, an ideal control cannot be achieved either before or after retrofit, therefore a really useful effect can be obtained only during that period when the temperature in apartments does not exceed the upper limit of comfort (24°C[8]), otherwise the tenants are going to do more intensive airing of the rooms. In this situation, a slightly different formula is used for calculation of the true useful effect dQi':

$$dQi' = (Qhd' - Qhd'')*(Tap^n - Tos^u)/(Tap^n - Tos^d)*Z^u, \quad (7)$$

where

Tos^u – average outside air temperature over the days during which the temperature in apartments of a retrofitted building did not exceed the upper limit of comfort;

Z^u – duration of the period during which the temperature in apartments of a retrofitted building did not exceed the upper limit of comfort.

An approach has been developed within the framework of this task, making it possible to determine with a high accuracy the actual heat demand of a building, which may significantly differ from the design value owing to alterations of process engineering during construction of the building, wear of structural members, etc. Its core is that actual heat demand is determined using the data on heat consumption in the SH system, outside and inside air temperatures for the period within the optimal range of inside air temperatures[9]. Under this approach the true impact of the space heating system equipment on the temperature in apartments is found, because the probability of heat gains from the other facilities (gas supply and power systems) within the optimal range of inside air temperatures is minimal.

Estimation of untapped energy-saving potential

The energy-saving potential may be determined for a building both prior to the retrofit (anticipated effect), and following the retrofit (untapped energy savings). Presence or absence of this potential is related to the possibility of improving control of heat delivery to the building. Quantitative assessment of the potential was done as far as the lower and upper limits of comfort. The calculation algorithm for the potential is as follows:

1. Based on actual heat demand and average daily data on the outside air temperature over the calculation period, the daily heat consumption for space heating (before and after retrofit) required to maintain in apartments either the standard air temperature of 18/20°C (lower boundary of comfort) or the maximum permissible temperature of 24°C (upper boundary of comfort) is estimated.
2. The difference is found between the real and estimated heat uses (before or after retrofit) for each day.
3. The potential for saving is found as the sum of differences between daily values of real and estimated heat uses over those days when the average temperature in apartments of the building (before or after retrofit) exceeded the standard value (for assessment of the potential as far as the lower boundary of comfort) or the upper permissible value (for assessment of the potential as far as the upper boundary of comfort). This procedure makes it possible to account for occurrence of underheating in buildings and unequivocally interpret the available results as an estimate of the possible reduction of heat consumption due to better control of the load.

Calculation of specific indicators for heat and water use

Calculation of specific thermal characteristic of the building - q_o [kcal/(m³.h.K)] was according to the formula:

$$q_o = Qht^a/(0.99VhZ(Tap^n - Tos^h)\ 4.187x10^{-6}), \quad (8)$$

where:

Qht^a – real annual heat consumption in the space heating system over a heating season, GJ;

Vh – heated volume of building (from external measurements), m^3;

0.99 – correction factor for the design temperature of outside air;

Z – duration of the heating season, hours;

$4.187x10^{-6}$ – conversion coefficient for kcal to GJ.

The specific heat use for space heating was also calculated on two different bases: referred to a unit of the total heated area of the building - q_h [kWh/m²], which reflects the existing level of heat use by the building for space heating regardless of the weather conditions and the comfort conditions; and referred to a unit of the total heated area of the building and the average degree-days in a heating season - $q_{h'}$ [Wh/(m².K.day)]. The characteristic $q_{h'}$ reflects the existing level of heat use by the building over a heating season taking into consideration the weather conditions and the conditions of comfort, also indirectly characterising the behaviour of tenants in the situation of existing underheating or overheating of their apartments. The calculations were done by formulae:

$$q_h = Qht^a*278/Ah, \quad (9)$$

where:

Ah – heated area, defined as the area of building floors measured within the confines of inner surfaces of external walls of the building (calculated as the footprint area multiplied by a factor 0.95), and

8. According to existing Russian standard documents (GOST 30494-96, 1999), the permissible range for air temperature in apartments is either 18-24°C or 20-24°C, which depends on the value of design outside temperature.
9. According to existing Russian standard documents (GOST 30494-96, 1999), the optimal range for air temperature in apartments is either 20-22°C or 21-23°C, which depends on the value of design outside temperature.

$$q_{h'} = Qht^{a} *278000/(Ah*(Tap^{n} - Tos^{h})*Z/24) \qquad (10)$$

Specific indicators of water use were defined as average daily specific consumptions of hot and cold water per tenant [l person per day].

The next section gives information about the results obtained using the methods described above.

Results on heat and water savings obtained

In order to systematize the results, buildings in each city were subdivided into groups having the same retrofit packages.

An analysis of results obtained has revealed a great scatter of the values for savings, even in buildings in one group, which points to their different status at the start of retrofit activities. In view of the great diversity of buildings and retrofit packages, we restrict ourselves to a representation of the range and the mean values for every component of effect obtained in cities.

Effect derived from commercial metering

The difference between the standard and the measured heat consumptions at the buildings under survey is in the range from –39% to 16% (DHW system) and from –37 to 18% (SH system)[10]. At the same time, for most cities the mean value of mismatch between the standard and the measured heat consumptions does not exceed 8-9%. Table 2 contains the data on the difference between the standard and the measured consumptions of heat and water arrived at as a result of calculations by formula: $(Q(V)^{n} - Q(V)')/ Q(V)^{n}$.

The difference between the standard and the measured consumptions of heat and water is due to instability of heat supply, inadequate central control, as well as errors in data used by heat supply companies to determine the standard values for heat supply to meet the heat demand of buildings.

Please note that with a big scatter of results obtained for individual buildings, the average saving (values of dQm) are relatively low. This may be explained by the existing practice of settling accounts with the heat supply companies, when only the total delivery of heat to all consumers is monitored, whereby the inaccuracies in determining the heat consumption to individual buildings are of little importance.

The scatter of results from individual buildings obtained for the water supply system is from –124 to 30% (DHW) and from –72 to 117% (CW). Any big deviations of the measured consumptions for hot and cold water from the standard values, which have been obtained for some buildings, may be due to inaccuracy of the official data about the number of residents in these buildings. Deviation in the aggregate indicators for cities is due to inappropriate standards, as well as to the DHW system not operating to specification, in particular allowing the DHW to exceed (by 30 – 40°C) or fail to reach (by 15 – 25°C) the standard temperature.

Direct savings of water

Water saving at buildings is from –22% to 27% (DHW system) and from –20% to 26% (CW system). A big scatter of results may be explained by a different set of implemented retrofits, different operating conditions and the condition of DHW and CW systems prior to retrofit. Maximum savings have been obtained at buildings, where apartment water meters were installed. Savings at these buildings amounted to 26% for cold water and 27% for hot water. Please note that the meters were installed for the purpose of technical metering only. Therefore, it may be assumed that in the case of their use for commercial metering the existing potential for water saving will be considerably higher. Table 3 shows average results for water savings by city.

Table 2. Difference between standard and measured consumptions of heat and water.

City	Heat consumption			Water consumption		
	DHW	Space Heating	Total	DHW	CW	Total
Cherepovets	-55.2%	-16.4%	-31.7%	-11.6%	13.4%	3.4%
Orenburg	2.5%	-2.7%	-1.0%	-4.0%	-0.5%	-2.6%
Ryazan	5.4%	12.4%	8.7%	-50.3%	29.6%	3.6%
Vladimir	-7.8%	-9.2%	-8.0%	-2.6%	19.1%	9.7%
Volkhov	14.7%	-0.4%	6.6%	-0.3%	6.7%	5.3%
Petrozavodsk	-17.0%	10.0%	-1.0%	-16.4%	5.8%	-3.5%

Table 3. Water savings.

City	Water savings		
	Hot water, %	Cold water, %	Total, %
Cherepovets	2.0%	2.9%	2.5%
Orenburg	13.0%	9.7%	11.3%
Ryazan	5.3%	0.2%	1.4%
Vladimir	-3.4%	-1.0%	-1.5%
Volkhov	-2.0%	4.3%	2.6%
Petrozavodsk	1.9%	-1.6%	-0.3%

10. A negative percentage means that actual heat consumption in buildings before retrofits is more than standard.

Table 4. Effects derived from retrofits in heat supply systems of buildings.

City	Space Heating, %				DHW, %	Total savings obtained, %	Total savings (including potential), %
	Direct savings	Indirect savings	Potential savings (up to top comfort level – 24°C)	Potential savings (up to bottom comfort level – 18 or 20°C)	Direct savings		
Cherepovets	2.6%	1.2%	2.0%	22.9%	4.4%	**8.2%**	**33.1%**
Orenburg	4.6%	1.5%	0.9%	12.1%	3.7%	**9.8%**	**22.8%**
Ryazan	5.3%	1.5%	0.0%	4.2%	1.5%	**8.3%**	**12.5%**
Vladimir	3.5%	6.7%	0.5%	23.4%	4.9%	**15.1%**	**39.0%**
Volkhov	3.2%	2.5%	0.0%	9.1%	7.5%	**13.2%**	**22.3%**
Petrozavodsk	2.3%	0.4%	0.6%	14.9%	0.0%	**2.7%**	**18.2%**

Table 5. Information about comfort conditions in buildings under survey.

City	Duration of different comfort conditions, %					
	Before retrofits			After retrofits		
	Underheating (<18/20°C)	Standard (18/20 – 24°C)	Overheating (>24°C)	Underheating (<18/20°C)	Standard (18/20 – 24°C)	Overheating (>24°C)
Cherepovets	7.4%	66.8%	25.8%	11.0%	74.4%	14.7%
Orenburg	4.9%	72.9%	22.2%	11.9%	83.4%	4.7%
Ryazan	59.6%	40.1%	0.2%	51.7%	48.3%	0.0%
Vladimir	2.6%	86.9%	10.5%	6.8%	88.9%	4.3%
Volkhov	11.7%	85.1%	3.2%	3.1%	95.8%	1.2%
Petrozavodsk	32.7%	64.6%	2.7%	28.0%	70.1%	2.0%

Significant water savings have been recorded in one city only (Orenburg), where the recirculation line was restored. In other cities, the aggregate effect is insignificant.

Direct heat savings

Heat savings at buildings amount to between 0% and 23% (DHW system) and from –4% to 37% (SH system). The big scatter of results may be explained by different sets of retrofits implemented, different operating conditions and the condition of buildings and in-house engineering systems prior to retrofit. Table 4 contains information with the results obtained.

Since obtaining direct heat savings in the SH system involves better control over heat delivery to the building, maximum direct heat savings in the SH system have been obtained at buildings where overheating prevailed prior to retrofit. In the DHW system, the maximum effect has been achieved at buildings, where the DHW temperature prior to retrofit considerably exceeded the standard level, and also where the recirculation line was restored during retrofit. Lack of savings or even increased consumption of heat was recorded at the buildings where the works on installation of automated IHS had still not been completed during the measurement program.

Indirect heat savings

The average effect of improved comfort does not exceed 7% (see Table 4). This is due to the fact that expensive complex solutions on thermal insulation of buildings (window replacement, additional insulation of the walls) was used to a limited extent and only for the buildings in urgent need of such work.

Untapped energy-saving potential

Table 4 shows the values of the untapped potential at retrofitted buildings to lower and upper boundaries of comfort.

Availability of a big untapped potential is due to lack of good adjustment for controllers and new equipment. This situation may be explained by insufficient experience of the staff of municipal maintenance organizations and lack of qualified specialists.

Data on thermal comfort in retrofitted buildings prior to and following retrofits supplement the above-given results on indirect and potential savings. Most clearly the temperature level in apartments before and after retrofits may be demonstrated by the example of the duration of the apartment temperature staying in this or that state of comfort (see Table 5). The results are expressed as a percentage of the whole heating season for each city.

Calculation of specific indicators for heat and water use

The values obtained may be useful when developing standard documentation on thermal protection of buildings under different operating conditions. The values of specific indicators, averaged by cities, are shown in Table 6.

Summary information on real values of specific characteristics applied during the settlement of payments with the tenants, and the data on the share of heat use in the DHW system as a fraction of the total heat use, are given in Table 7.

Table 8 gives the information on the average specific consumptions of water by cities.

Table 6. Specific indicators of heat consumption for SH.

City	Before retrofits			After retrofits		
	kcal/(m^3.h.K)	kWh/m^2	Wh/(m^2.day.K)	kcal/(m^3.h.K)	kWh/m^2	Wh/(m^2.day.K)
Cherepovets	0.44	172.5	36.1	0.43	167.0	34.9
Orenburg	0.46	158.6	36.0	0.44	151.7	34.5
Ryazan	0.34	99.0	27.2	0.29	84.0	23.1
Vladimir	0.46	136.8	36.6	0.43	126.9	34.1
Volkhov	0.47	153.7	37.6	0.44	145.8	35.6
Petrozavodsk	0.32	111.5	25.9	0.31	107.8	25.0

Table 7. Specific indicators of annual heat consumption for SH and DHW.

City	Heat consumption in DHW system, GJ/tenant per year		Heat consumption in space heating system, GJ/m^2 per year		Share of heat consumption in DHW system, %	
	Before retrofits	After retrofits	Before retrofits	After retrofits	Before retrofits	After retrofits
Cherepovets	13.7	12.7	0.62	0.60	45.6%	43.3%
Orenburg	10.7	10.0	0.57	0.55	44.0%	43.8%
Ryazan	10.6	10.5	0.36	0.30	55.7%	59.3%
Vladimir	10.8	10.1	0.49	0.46	46.8%	45.3%
Volkhov	11.2	9.0	0.55	0.52	44.1%	40.5%
Petrozavodsk	12.5	11.9	0.40	0.39	53.5%	54.0%

Table 8. Specific indicators of water consumption.

City	DHW consumption, l/tenant per day		CW consumption, l/tenant per day		Total water consumption, l/tenant per day	
	Before retrofits	After retrofits	Before retrofits	After retrofits	Before retrofits	After retrofits
Cherepovets	134	142	156	156	290	298
Orenburg	154	139	171	148	325	287
Ryazan	158	153	153	149	311	302
Vladimir	123	133	146	163	269	296
Volkhov	120	119	187	158	307	278
Petrozavodsk	122	119	160	196	282	315

Conclusions

Under this work unique experience of implementing a program of measurements on operating parameters in a big number of type multi-family residential buildings in Russia has been accumulated. A systematic approach to processing and analysis has been developed, based on a very large volume detailed information about the building heat and water use before and after retrofits. The following main results have been obtained:

- The actual value has been determined for the use of heat and water by buildings under various operating conditions;
- An analysis has been carried out to review the impact of the outside air temperatures, inside air conditions, and operating conditions for the heat and water supply system on the building heat and water use modes;
- The realized effectiveness of various building retrofit technology packages has been determined and the effect from individual groups of retrofits has been evaluated;
- The value for untapped potential heat savings has been defined for buildings and the reasons for availability of this potential have been identified.

The approaches developed within the framework of measurement program implementation, and the results obtained have expanded the applicability of the AuditHelp program (Komarov, 1999) and secured the performance of the following functions:

- Application in evaluating the effectiveness of various retrofit packages in terms savings obtained in practice for heat and water;
- Carrying out an analysis of the heat consumption level and of the potential for savings derived from various passive and active retrofit technologies with a minimum amount of initial data and over the shortest possible period;
- Monitoring the effect obtained on a building after retrofits with a view to taking timely action toward generating maximum benefit from the retrofits implemented.

Implementation on buildings of the existing potential for heat and water saving, while continuing the program of measurements, as well as an upgrade and verification of the AuditHelp program are the evident follow-up steps that are scheduled for implementation at the concluding stage of the Project. Following completion of the Project, the obtained data will be systematized and made available to the organizations active in the field of municipal management and communal heat supply.

References

Collected TAG-2 technical reports "Progress, results and effectiveness of EHDP", Volume I "Energy saving in multi-storey residential buildings", Report "Estimation of energy saving retrofits", EHDP, TAG-2, 2001.

Conception of heat supply development in Russia including communal energy on medium-term outlook, Official information of Minenergo RF, Moscow, Russia, 2002. (In Russian).

E.Y. Sokolov "Cogeneration-based district heating and heat network". - M.: MPEI publisher, 1999 (In Russian).

GOST 30494-96 "Residential and public buildings. Microclimate parameters for indoor enclosures", appr. Gosstroy RF, 1999. (In Russian).

O.V.Komarov. "AuditHelp computer program", EHDP, Newsletter, issue VII, 1999.

Report on Data Collection, EHDP, Battelle, Pacific Northwest Division, 1998.

Acknowledgements

We are very grateful to experts in consulting groups TAG-1 (Battelle Memorial Institute, Richland, WA, USA), TAG-2 (Consortium of companies InnoTec Systemanalyse GmbH, Germany, The Institute for Maintenance and Modernization of Buildings, Germany and Building Research Establishment Limited, United Kingdom), TAG-3 (Company "Enizan", Russia), which were participating in this work during 1996-2002.