RIGA TECHNICAL UNIVERSITY

Dzintars Grasmanis

# ENERGY PERFORMANCE ASSESSMENT OF DOMESTIC HOT WATER SYSTEMS OF APARTMENT BUILDINGS

Summary of the Doctoral Thesis

RTU Press
Riga 2018

RĪGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Heat, Gas and Water Technology

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**DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES**

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 13 December 2018, at Riga Technical University, 6 Azenes Street, Conference Room.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Dzintars Grasmanis ______________________ (Signature)

Date: _________________

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 5 chapters; Conclusions; 57 figures; 19 tables; and 1 appendix; the total number of pages is 102. The Bibliografy contains 101 titles.

# CONTENT

# Introduction

**The importance of the topic**

Multi-apartment buildings are one of the largest group of district heat users in Latvia. The residential sector consumes 70 % of the total heat produced in district heating systems in Latvia. The amount of energy consumed in domestic hot water (DHW) systems represents an average of 51 kWh per square meter of apartment's heated area annually or 27 % of the total heat energy consumption in those buildings.

To implement the goals of the European energy policy The Energy Performance of Buildings Directive has been adopted that introduced energy performance certification of the buildings. According to the European Commission mandate M480 a number of European standards for the assessment of the energy performance of buildings – EPBD standards have been developed and adopted. The EPBD standards prescribe that EU member states shall adopt the standards at national or regional level, taking into consideration local climatic conditions. The EPBD standards adopted for Latvia (LVS) are not supplemented with national annexes necessary for full application of the standards at national level.

Previous studies carried out in various European countries, China, Japan, the USA, and Canada point out many differences in DHW usage and consumption as well the tendency to change over time due to a global increase of energy prices, changes in technologies, introducing of individual metering, as well as wide variety of other factors that may appear at local or regional level. Regional and local differences may be caused by different living standards, season of the year, different lifestyle in urban and rural areas. During the last decades, substantial changes in domestic hot water consumption are observed in Eastern European countries. Studies in Estonia show that household hot water consumption has decreased more than three times during the last 30 years, which is caused by the implementation of water consumption metering, increase in energy price and implementation of energy efficiency measures in the buildings. The Latvian researchers' study on DHW consumption profiles in apartment buildings found that the actual consumption of DHW is twice lower than the normative. Energy needs for the DHW represent significant part of energy balance of residential and some other sectors of buildings. Significant amount of energy demand can be caused by both DHW consumption needs and DHW circulation losses.

The scientific and technical articles provide wide and overall information on DHW systems, consumption profiles, technologies and technical solutions. Taking into consideration changeable political, economic, technological circumstances and legal conditions as well as local or regional factors the necessity for more and more new studies on DHW systems still exists.

**The goal of the Doctoral Thesis**

The goal of the Thesis is to assess the applicability of EPBD standards for Latvian conditions and to find the right solutions (methods and default values) for calculation of energy performance indicators of the DHW system for energy certification of buildings. Accurate calculation of energy balance of buildings is the basis for proper assessment of energy performance indicators.

**The tasks of the Doctoral Thesis**

Usually apartment buildings have a single heat meter for both heating and DHW in Latvia. Therefore to calculate energy performance indicators of a building, it is necessary to assess the volumes of the DHW, the energy required for DHW heat at the required temperature, and thermal losses in the DHW distribution and circulation pipelines. In this study the assessment of the consumption of heat energy in apartment buildings for heating and hot water system is performed. The study includes the following assessments: 1) assessment of the DHW volume and necessary energy amount;

2) assessment of heat losses in the hot water distribution system during heating and non-heating seasons;

3) assessment of auxiliary energy of the DHW system.

Based on experimental results the applicability of calculation methods of European standards in Latvian conditions is tested.

**Research methodology**

The study analyses the heat energy consumption and DHW volume consumption in apartment buildings in Riga city and Bauska town. The aggregated data contains information on 39 apartment buildings with total heated area of 158 thousand m$^2$ in Riga, and 57 apartment buildings with total heated area of 91 thousand m$^2$ in Bauska. All buildings have been constructed by standard type designs from nineteen sixties until nineteen nineties and are connect to the centralised district heating networks.

Within this study an assessment of heat consumption in the DHW system and evaluation of energy performance indicators based on EPBD standards was performed.

**Scientific novelty**

During the study, energy performance assessment and calculation methods of the EPBD standards for DHW systems of apartment buildings in Latvia were tested. The study offers a method applicable in Latvian conditions.

**The practical value of the Doctoral Thesis**

The results of this study provide an evaluation of the representative DHW consumption and energy performance indicators in apartment buildings.

The study shows measurement based data and the results suitable for the development of a method for calculation of energy performance of DHW systems adjusted to Latvian conditions and the adoption of EPBD standards at national level.

The results of Doctoral Thesis provide the base for economic and energetic evaluation of possible improvements of DHW systems of buildings.

**The approbation of the results of the Doctoral Thesis**

The results of the Doctoral Theses are reflected in 9 scientific publications, as well as reported in 8 international conferences.

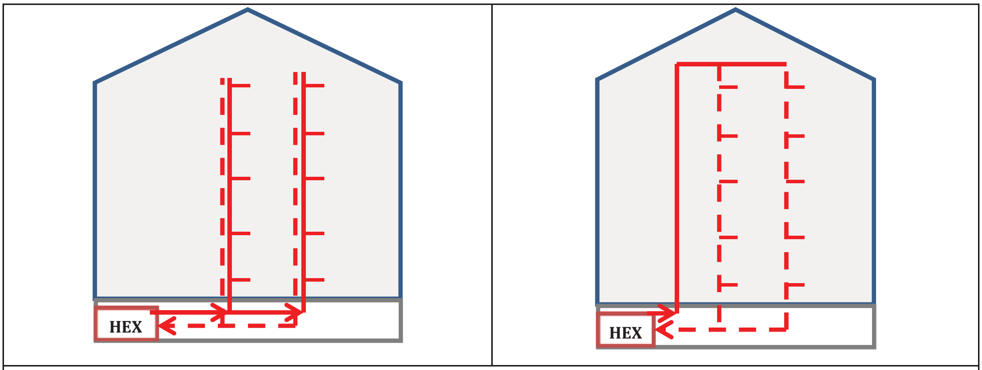
# 1. Assesment of energy performance of DHW systems of apartment buildings

## 1.1. Materials and methods

Within this study, heat energy and hot water consumption in multi-apartment buildings is analysed. Taking into consideration that the water consumption in individual households may significantly differ, multi-apartment buildings of standard type of design with a large number of apartments were selected for this study. This approach smoothes out the differences and gives higher validity of results to characterise the appartment housing sector. The selected multi-apartment buildings have a typical annual heat consumption (for Latvian climate conditions). The buildings have been operated for a long time without any reconstruction, except automatic heating units improved about 10 to 15 years ago in most buildings. The annual thermal energy consumption in the analysed buildings ranges from 164 to 225 kWh/m$^2$ in Riga and from 155 to 245 kWh/m$^2$ in Bauska (both calculated for total dwelling area).

The study covers 3 to 12-storey buildings in Riga city and Bauska town. The total heated area of the 39 buildings is 158 194 m$^2$ in Riga, in these buildings there are 3359 households (dwellings) and 7139 inhabitants. The total heated area of the 57 building is 91 001 m$^2$ in Bauska, in these buildings there are 3167 households (dwellings). The author does not have data on the number of inhabitants of buildings in Bauska. The investigated buildings are built according to standard type designs of the sixties to nineties of the 20th century.

All investigated buildings are connected to the district heating network. All buildings have the automatic heating unit equipped with a single heat meter for heating and DHW as well as hot water and cold-water meters. Automatic heating control unit ensures DHW temperature of about 50 to 55 °C during the water taping. The draw of DHW distribution systems with circulation is shown in Fig. 1.1. For most of the standard design type buildings (except for 12-storey design type No. 104) the DHW distribution system has several circulation loops with bottom distribution supply pipes from the basement, branch pipes from supply pipes in dwellings and downward return pipes. The DHW distribution system of 12-storey design type No. 104 buildings have one upward supply pipe from basement to the top of the building (attic) and several downward return pipes with branch pipes in dwellings.




supply pipes, return pipes

HEX – heating unit (heat exchanger)

Fig. 1.1. DHW distribution system with circulation loop. The bottom distribution (on the left), the upper distribution (on the right).

The European standards adopted in relation to energy performance of buildings provide concept and common methods for preparing energy performance certification and energy inspections of buildings. The calculation model for energy performance assessment of DHW systems is described by the following standards.

1. EN 15316-1 – Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 1: General (EN 15316-1).
2. EN 15316-3-1 – Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 3–1: Domestic hot water systems, characterisation of needs (tapping requirements) (EN 15316-3-1).
3. EN 15316-3-2 – Heating systems in buildings. Method for calculation of system energy requirements and system efficiencies. Part 3–2: Domestic hot water systems, distribution (EN 15316-3-2).

## 1.2. Characteristics of domestic water consumption

The assessment of the consumption data per dwelling area in 22 buildings in Riga shows that the average annual consumption of water in the investigated buildings is 3.64 litres per $m^2$ daily, of which 2.12 litres of cold water and 1.52 litres of hot water. The average daily consumption of domestic cold water and DHW per $m^2$ per day shown in Fig. 1.2. The chart shows that the consumption of hot water decreased but consumption cold water increased during the summer.

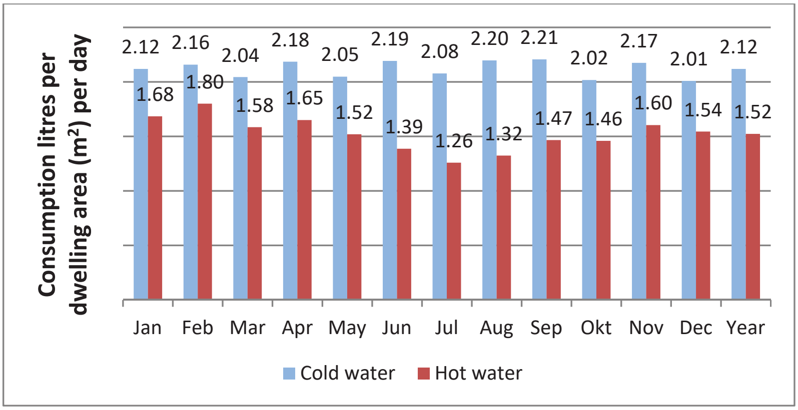



Fig. 1.2. Average daily consumption of domestic cold water (DCW) and domestic hot water (DHW) in apartment buildings (litres per $m^2$ per day) by months and yearly.

The average DHW consumption ratio is 41.8 % of total annual water consumption while seasonally it is 43.9 % during heating season and 39.4 % during non-heating season. Figure 1.3 shows DHW consumption ratios of total and inlet water average temperature variations per month. The monthly differences of hot water consumption ratio are caused by variation of temperature of inlet cold water during a year. When supplied cold-water temperature increases (in summer), the necessary hot water amount decreases, whereas when the supplied cold-water temperature decreases (in winter), the necessary hot water amount increases. DHW consumption is 94 % of annual average in the non-heating season and 106 % of annual average in the heating season.

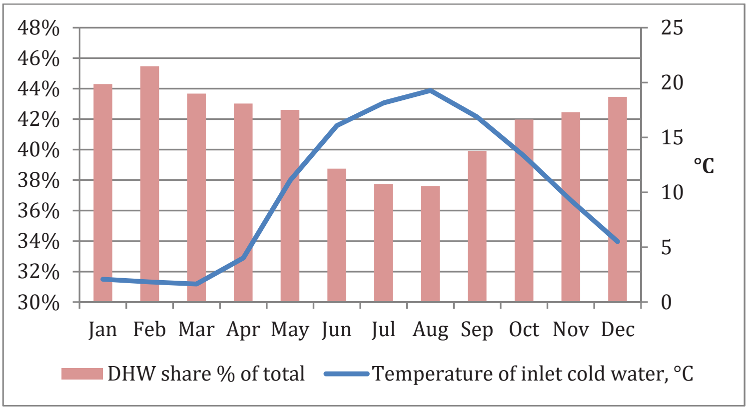



Fig. 1.3. The ratio (%) of consumption of DHW to the total consumption in apartment buildings and average temperature of inlet cold water per month.

The study shows specific DHW consumption indicators (Table 1.1) – the consumption of DHW litres per day per dwelling area (m$^2$), per household, per person (one inhabitant), and the coefficient of determination ($R^2$) of all indicators. The coefficient of determination is used to explain how much variability of one factor can be caused by its relationship to another factor (if the coefficient is closer to 1 then the relationship is closer). Consequently, the DHW consumption per one inhabitant has the highest coefficient of determination ($R^2 = 0.94$).

Table 1.1

DHW Consumption Indicators

| | | Minimum | Maximum | Average | Coefficient of determination $R^2$ |
|---|---|---|---|---|---|
| **Consumption of DHW, litres per day** | | | | | |
| **Per m$^2$ of dwelling area** | Riga | 1.10 | 2.73 | 1.86 | 0.90 |
| | Bauska | 1.01 | 3.53 | 1.54 | 0.84 |
| **per dwelling (household)** | Riga | 55.7 | 142.6 | 94.0 | 0.88 |
| | Bauska | 40.0 | 121.3 | 73.1 | 0.81 |
| **per person** | **Riga** | 24.2 | 60.2 | 41.0 | **0.94** |

By comparing DHW consumption indicators in the investigated buildings to default values set out in Annex A of standard EN 15316-3-1 the author found out that the average DHW consumption of 41.0 litres per person per day is close to the default value of 36 litres per person per day in Table A.1 'Tapping program No. 1'. In addition, DHW consumption significantly differs from the values set by Latvian Construction standard LBN 221-15 “Internal Water-main and Sewage of Buildings”. The paragraphs 1.6 to 1.8 of Annex 4 of LBN 221-15 set the DHW consumption normative values of 85 to 105 litres per person per day. The consumption values of LBN 221-15 are equivalent to the values specified in the former USSR Standard *СНиП 2.04.01-85 «Внутренний водопровод и канализация сданий»* (in Russian).

The average value of DHW consumption of 94.0 litres per dwelling in Riga and 73.1 litres per dwelling in Bauska are lower than the default value of 100.2 litres per dwelling, determined in Table A.2 (‘Tapping program No. 2.’) and is very different from the default value of 199.8 litres per dwelling, determined in Table A.3 (‘Tapping program No. 3.’).

### 1.3. Assessment of energy consumption in DHW subsystems

To calculate the energy used for DHW needs and DHW circulation, the data on heat energy consumption in the buildings during non-heating season (May to September) is used.

In general, the total heat energy consumption $Q$ in the analysed building is the sum of energy for heating, DHW needs, and heat losses in the DHW distribution circulation loop.

$$Q = Q_H + Q_W + Q_{W,cirk} \tag{1.1}$$

where $Q$ is the total energy consumption for heating and for DHW system, kWh; $Q_H$ is the energy consumption for space heating, kWh; $Q_W$ is the energy consumption for DHW needs, kWh; $Q_{W,cirk}$ is thermal losses from pipes of DHW distribution circullation loop, kWh.

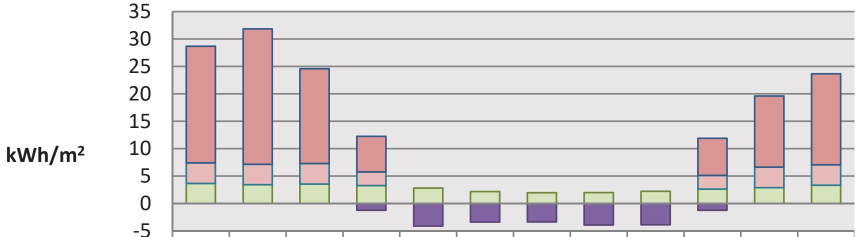
The energy need for DHW heating $Q_w$ is calculated as follows:

$$Q_w = V_W \frac{\rho_w C_w}{3600}\left(\theta_{w,del} - \theta_{w,o}\right) \tag{1.2}$$

where $Q_w$ is the energy need for DHW, kWh; $V_w$ is the volume of water (in the respective period), m$^3$; $\rho_w$ is the density of water, kg/m$^3$; $C_w$ is the specific heat capacity, J/(kg·K); $\theta_{w,del}$ is the average cold water inlet temperature, °C; $\theta_{w,o}$ is the average DHW delivery temperature, °C; 3600 is the factor of conversion from megajoules to kilowatt-hours.

The calculations of the study are based on actual monthly average cold water temperatures. For comparison, the calculations based on seasonal (heating and non-heating season) average cold water temperatures or default cold water temperatures from LBN 221, have impact on the results within 2 %. The calculation with average annual default cold-water temperature (either LBN 221 or EN 15316-3-1) affect the results more and the error may exceed 10 %.

Based on the data of energy necessary for DHW needs during non-heating season, it is possible to calculate the energy losses in DHW distribution circulation loop. The calculated monthly data of energy consumption for DHW needs (consumption), the thermal loses in DHW circulation loop and the energy for heating system per dwelling area of buildings in Riga is shown in Fig. 1.4.




| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Heating needs | 21.29 | 24.68 | 17.29 | 6.49 | | | | | | 6.77 | 12.98 | 16.59 |
| Recoverable DHW circulation losses (heat gains) | 3.74 | 3.74 | 3.74 | 2.49 | | | | | | 2.49 | 3.74 | 3.74 |
| Non-recoverable DHW circulation losses | | | | -1.25 | -4.12 | -3.40 | -3.37 | -3.93 | -3.88 | -1.25 | | |
| DHW needs | 3.66 | 3.42 | 3.55 | 3.26 | 2.82 | 2.19 | 1.95 | 2.00 | 2.23 | 2.63 | 2.89 | 3.32 |

Fig. 1.4. Average values of heat energy per $m^2$ of heated dwelling area per month for heating, DHW needs, DHW circulation (data on 39 buildings in Riga).

The total thermal losses of a DHW distribution circulation loop range from 28.9 to 65.2 kWh per $m^2$ per dwelling area annually for different standard design buildings. The average thermal losses of a DHW distribution circulation loop are 45.4 kWh per $m^2$ per dwelling area annually for buildings in Riga, and 53.5 kWh per $m^2$ per dwelling area annually for buildings in Bauska.

The assessment of thermal losses in DHW circulation loop in different standard design buildings per apartment give values ranges from 1.1 MWh to 3.0 MWh per annum or 0.1 MWh to 0.25 MWh per month. For buildings in Riga the average value is 2.28 MWh per apartment per annum or 0.18 MWh per month, for buildings in Bauska the average value is 2.58 MWh per apartment per annum or 0.21 MWh per month. In most buildings, monthly thermal losses in DHW circulation loop significantly exceed the default value (0.1 MWh per apartment per month) recommended for settlement calculations in Riga city.

During heating season, the heat losses from the DHW circulation loop are recoverable for heating needs. Thus, during the heating season the heat losses in DHW circulation system are heat gains as part of total heating balance of the building.

During non-heating season, all thermal energy consumption is used only in DHW system of building. The study shows that the share of heat losses in DHW circulation loop ranges from

35 % to 79 % (56 % on average) of total energy consumption or from 14.9 to 25.6 (20.2 on average) kWh per m$^2$ annually during non-heating season in investigated buildings in Riga.

Heat losses in the DHW circulation system have close correlation to the heated area of the building, but there is also a correlation in relation to the number of apartments, as well as number of circulation loops. Simultaneously the study shows that there is no correlation between heat loss in DHW circulation loop and such characteristic of building as: dwelling area, number of apartments, number of inhabitants (Fig 1.5), i.e. variables that have close correlation to DHW consumption.

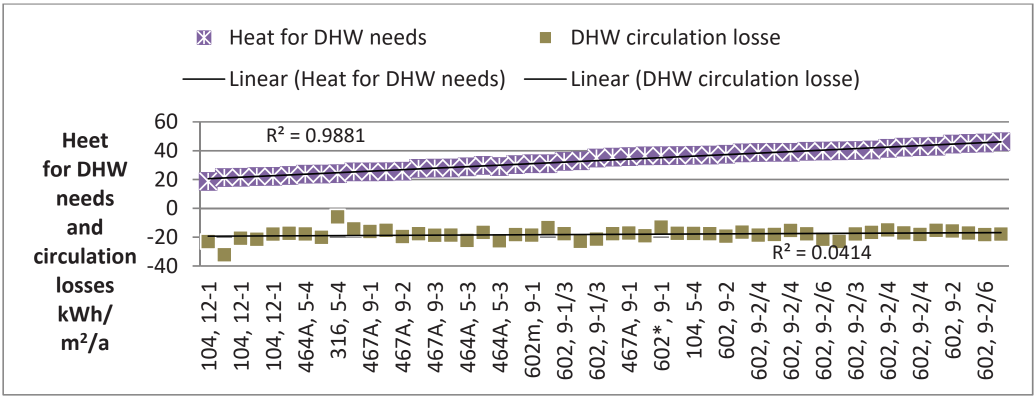



Fig. 1.5. Heat consumption for DHW needs and DHW circulation losses (data on 39 buildings in Riga arranged by heat consumption for DHW needs)

## 1.4. Calculation of heat energy losses based on actual physical characteristics of DHW pipes

Estimation of thermal energy losses in the DHW distribution system (experimental data), which were assessed based on actual measured data for heating and DHW volume consumption in the building (see Section 1.3), in the study were compared with the results obtained according to the following methods:

1) calculation of thermal losses based on physical characteristics of DHW pipeline according to 6.3.3. of Standard EN 15316-3-2 using standard values provided in Annex D of the standard;
2) calculation of thermal losses based on the physical characteristics of DHW pipeline according to 6.3.3. of the standard EN 15316-3-2 using the values proposed by the author.

The general determination of thermal losses of a circulation loop comprising a number of pipe section $i$ is given by the following equation:

$$Q_{w,dis,ls,col} = \sum_i Q_{w,dis,ls,col,i} = \sum_i \Psi_{W,i} L_{W,i} \left(\theta_{W,dis,avg,i} - \theta_{amb,i}\right) t_W \quad (1.3)$$

where $Q_{w,dis,ls,col,i}$ is specific energy losss of the distribution of pipe section $i$, Wh; $\Psi_{w,i}$ is linear thermal transmittance of the respective pipe section $i$ (W/(m·K)); $L_{w,i}$ is length of the distribution pipe section $i$ (m), $\Theta_{w,dis,avg,i}$ is mean inner temperature (water temperature) of pipe section $i$ (°C); $\Theta_{amb,i}$ is ambient temperature for the pipe section $i$ (°C); $t_w$ is period of the time that the heat loss shall be calculated for $\Theta_{w,dis,avg,i}$ (hours).

The DHW circulation system of investigated buildings has the following features: a) vertical distribution with known number of circulation loops in building section for each building type; b) he circulation loops run continuously all the time; c) each apartment has one towel rail on the circulation loop.

The DHW distribution system comprises three different pipe sections: $V$ – distribution pipes from heat exchanger to the vertical supply pipes on basement; $S$ – main supply pipes on building heated area that comprise vertical pipes (S1) and individual tower rails in the apartments (S2); $I$ – individual branching pipes to the user outlets in dwellings. Heat losses from individual branching pipes do not affect overall circulation losses. Heat losses from individual branching pipes is part of the heat energy for DHW consumption needs.

The author has developed unified formulas for calculation of length of circulation loop sections for the investigated buildings. Based on technical design of different standard buildings the author accepted the values and unified formulas for the calculation of pipe length of each DHW circulations loop section (Table 1.2). For comparison Table 1.2 shows the default values and formulas of Annex D of standard EN 15316-3-2.

To compare different calculation models, the calculations use equal temperature characteristics for both the DHW temperature in the pipe sections and the ambient temperature around pipe sections. The default values of liner thermal transmittance of pipe sections and formulas for calculation of the length of the pipe sections of Annex D of EN 15316-3-2 were used for comparative calculation. This approach allows more accurately compare the author's calculation method with the methods of standard EN 151316-3-2.

According to the standard, the default linear thermal transmittance of pipe section should be chosen with respect to building area. The calculations with default values of the linear thermal transmittance 3.0 W/(m·K) of the main supply circulation pipe section in heated area of building give results, which significantly (more than 4 times) differ from the result of actual assessment.

Table 1.2

Values and Formulas for Calculation of Thermal Losses in the Pipe Sections of Domestic Hot Water Distribution

<table>
<tr><td>Default values from Annex D of standard EN 15316-3-2</td><td>Calculation values proposed by author</td></tr>
<tr><td colspan="2">Technical characteristics of distribution pipes</td></tr>
<tr><td>$V$ – insulated, $\Psi = 0.4$ W/(m·K)<br>$S$ – non-insulated, external,<br>$\Psi = 1.0–3.0$ W/(m·K)<br>the value $\Psi = 1.0$ W/(m·K) used in calculations</td><td>$V$ – insulated, steel, $\Psi = 0.4$ W/(m·K)<br>$S_1$, $S_{1,up}$, $S_{1,down}$ – non insulated, steel,<br>$\Psi = 1.0$ W/(m·K)<br>$S_2$ – non-insulated, steel towel rails,<br>$\Psi = 1.0$ (W/m·K)</td></tr>
<tr><td colspan="2">Length of pipe section (m)</td></tr>
<tr><td>For all buildings:<br>$L_V = 2L_B + 0.0125\, L_B B_B$<br>$L_S = 0.075\, L_B B_B n_f h_f$</td><td>For all types of standard design (except design No. 104 of 12-storey buildings):<br>$L_V = 2L_B + B_B n_{B,dis,col}$<br>$L_{S,1} = 2L_B n_f h_f n_{B,dis,col}$<br>$L_{S,2} = n_{dwelling} L_{towel\,rail}$<br>12-storey building of standard design No.104<br>$L_V = L_B + B_B n_{B,dis,col}$<br>(One) upward distribution pipe $L_{S1,up}$<br>$L_{S1,up} = L_B n_f h_f$<br>Downard distribution pipes $L_{S1,down}$<br>$L_{S1,down} = L_B n_f h_f n_{B,dis,col}$<br>$L_{S2} = n_{dwelling} L_{towel\,rail}$</td></tr>
<tr><td colspan="2">$\Psi$ –linear thermal transmittance of pipe section (W/m·K); $L_B$ – the largest extended length of the building (m); $B_B$ – the largest extended width of the building (m); $n_f$ –number of heated storeys; $n_{B,dis.col}$ –number of circulation loops in building; $h_f$ –height of the heated storeys (m); $n_{dwelling}$ –number of dwellings in the building; $L_{towel\,rail}$ – average length of towel rails in dwellings (m).</td></tr>
<tr><td colspan="2">The following conditions are used in calculations: the average temperature of DHW circulation system is +52 °C; ambient temperature around DHW pipes is +20 °C; calculation time period is 162 days per 24 hours.<br>The European standards define the following default values: the average temperature of DHW circulation system is +60 °C; ambient temperature around DHW pipes is +22 °C. The standard values are not used in calculations.</td></tr>
</table>

The results demonstrate that default values of the linear thermal transmittance set in standard EN 15316-3-2 are not applicable for the assessment of heat loss of DHW circulation subsystem. Thereby author used input value 1.0 W/(m·K) as the closest to the actual value for calculation of the linear thermal transmittance of the main supply circulation pipe section in heated area of investigated building. The comparison of the length of pipe sections by the actual and standard model showed that differences are less significant – length of the pipes located in the basement (section V) according to the standards have a length from 50 % to 90 % of the actual, while for other sections (S) the difference ranges from 110 % to 320 %.

The calculation results for circulation losses in different assessment methods differ for standard type buildings with different technical design (Fig. 1.6.)

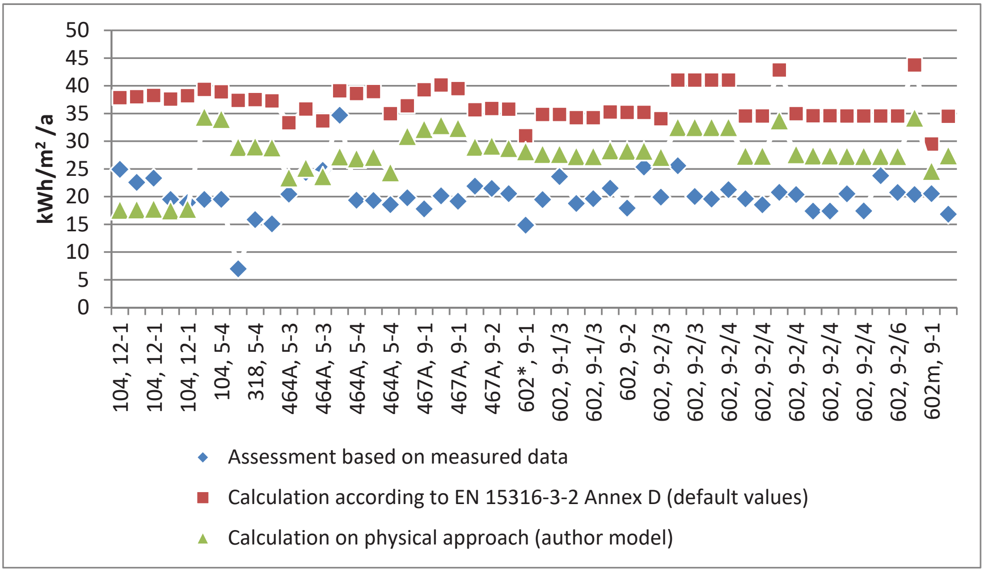



Fig. 1.6. Calculation results for circulation losses with different assessment methods.

The author believes that the most accurate results are based on actual measured data of heat energy and DHW volume consumption. The calculations based on metered data showed that thermal losses of a circulation loop range from 14.9 to 25.6 (20.1 on average) kWh/m$^2$/ per non-heating period (162 days) for the buildings in Riga and from 12.8 to 36.7 (23.7 on average) kWh/ m$^2$/ per non-heating period for the buildings in Bauska.

Based on the default values of technical characteristics of DHW system the calculation results in most cases significantly differ from the actual data (obtained during experiments).

The calculation of thermal losses based on physical characteristics of the actual DHW pipeline and calculation using standard values of the standard EN 15316-3-2 gives higher results than the experimentally based.

Theoretical calculations according to the author's methods give closer results to the experimental results that are obtained on measured heat energy and DHW consumption. The assessment results based on author's model differ from the experimental results in the range from 1 % to 88 % (44% on average) for different standard design buildings. In comparison, using default values and formulas for calculation, the difference is between 13 % and 147 % (81 % on average) for the buildings in Riga and from 11 % to 274 % (98 % on average) for the buildings in Bauska.

The author considers that the biggest differences between the calculation results based on physical approach and metered results were caused by the inappropriate default values of linear heat transmittance coefficient of pipe sections. Inaccuracy has formed, for example, due to embedding of pipes in the internal structures of the building. Therefore, the actual difference of the temperature of the pipeline and ambient temperature may significantly differ from the default data set to the standard. It is also known that technical design of some standard buildings have shared duct openings for DHW pipes and close sewage pipes that affects the surrounding temperature around the circulation pipes. The author considers that those errors can be prevented by a correction (reduction) of the default linear heat transmittance coefficient for vertical pipe sections. The study shows that the necessary corrections may significantly differ for buildings of different standard design.

## 1.5. Breakdown of heat loss by DHW circulation loop sections

Additionally, the author assessed circulation heat loss ratio of the DHW circulation systems by pipe sections during non-heating and heating seasons in different standard design buildings. This assessment is based on physical approach with actual technical characteristics of DHW circulation system. Equal conditions were used for calculations for heating and for non-heating seasons, with the exception of average ambient temperature (+20 °C for the non-heating season and +10 °C for the heating season) around pips in the basement.

The heat losses of DHW circulation loop outside the heating space (section V) are not recoverable during all of the year (on heating and non-heating season), while it is acceptable that the heat losses from towel rails (S2 section) are useful heat gains for comfort in the bathrooms throughout the year. However, heat losses from the vertical distribution circulation pipes (section S1) are useful heat gains (recoverable heat losses) during the heating season but not recoverable during non-heating season.

Based on the calculation model, the following rates were obtained for different pipe sections of the DHW system:

1) for pipes in non-heated basement − from 10 % to 13 % during non-heating season and from 12 % to 16 % during heating season for 5 to 12-storey buildings, from 19 % to 24 % during non-heating season and from 24 % to 29 % during heating season for 3-storey buildings and modified 4 and 5-storey buildings of standard design type No. 103 in Bauska;

2) for vertical distribution pipes − from 50 % to 60 % for 3-storey buildings, and from 55 % to 60 % for 5-storey buildings, from 64 % to 67 % for 9-storey buildings, and from 48 % to 49 % for 12-storey buildings;

3) for individual towel rails in dwellings − from 16 % to 27 % in 3-storey buildings, from 30 % to 33 % for 5-storey buildings, from 22 % to 24 % for 9-storey buildings, and 38 % for 12-storeyd buildings.

The calculations show that representative non-recoverable energy losses of DHW circulation loop range from 16 to 24 (20 on average) kWh per $m^2$ per year in investigated apartment buildings. The result is representative according to considerations that non-recoverable energy losses are in the basement during whole year, in vertical distribution pipes during non-heating season, but heat energy losses from towel rails are useful (no losses) during the whole year.

## 1.6. The assessment of the auxiliary energy of DHW system

Auxiliary energy is one of the indicators that should be calculated during the assessment of energy performance of the building. The auxiliary energy of DHW system can be calculated according to the following methods given in European or DIN[1] standards:

1) DIN V 18599-8:2007-02;

2) EN 15316-3-2:2008 (standard gives two methods: simplified and detailed);

3) EN 15316-1: 2017 and EN 15316-3: 2017.

In the investigated buildings, the auxiliary energy for the DHW emission sub-system, generation sub-system and storage sub-system is zero. Thus, during the study detailed calculations were done only for auxiliary energy for DHW distribution sub-system.

[1] DIN – Deutsches Institut für Normung (German Institute for standartization)

According to the simplified calculation method, the auxiliary energy for the pump can be calculated by multiplying the pump power with the pump operational running time. According to the detailed calculation method, the assessment of the auxiliary energy of the DHW system takes into account hydraulic energy requirements during the operation, performance characteristics of the circulation pump as well as more than 20 other technical characteristics of the buildings and DHW system.

The calculation of the auxiliary energy of the DHW system of the building by different European standard methods (simplified and detailed) gives similar results. The calculation according to simplified method shows that auxiliary energy of the DHW system ranges from 1.1 to 1.9 (1.5 on average) kWh/m$^2$/per year for different types of standard design buildings, while the calculation according to detailed method gives the results from 1.5 to 1.8 (1.6 on average) kWh/m$^2$/per year. The author finds that detailed calculation method is too complicated and time consuming. Therefore, the simplified method is recommended for use for the energy performance certification of buildings. As an alternative, the default value (for example, 2.0 kWh/m$^2$/per year) may be adopted at national level.

## 2. Recommendations for energy performance calculation model for the DHW system

The author suggests the method of unified accounting for heating and DHW needs for energy performance assessment of DHW system of the building. Detailed calculations can be carried out using the following algorythm.

1. The accounting data should be determined:
   a. the duration of the non-heating time period for month with no heating $t_{non\text{-}heating,count}$;
   b. total length of non-heating season $t_{non\text{-}heatin}$ ;
   c. energy consumption $Q_m$ for non-heating months $m$ and the sum of energy consumption during months with no heating $Q_{non\text{-}heating,count} = \Sigma Q_m$;
   d. the volume of DHW, $V_m$ , consumed during non-heating months $m$ and the sum of DHW volume consumed during months with no heating $V_{non\text{-}heating,count} = \Sigma V_m$.

(It is preferable to use the metering data from DHW meter of the whole building instead of the total sum of individual consumption data provided by the inhabitants of apartments).

2. The next step is the calculation of monthly energy consumption $Q_{W,m}$ necessary for DHW use during the months with non-heating (see Formula 1.2. in Section 1.3.) and the sum for the months with non-heating $Q_{W,\ non\text{-}heating,count}=\Sigma Q_{W,m}$.

3. Next is the calculation of thermal losses in the DHW circulation loops $Q_{W,dis,non\text{-}heating.count}$ for non-heating months according to the formula

$$Q_{W,dis,non\text{-}heating,count} = Q_{non\text{-}heating,count} - Q_{W,\ non\text{-}heating,count} \tag{2.1}$$

4. The energy for DHW needs $Q_{w,non\text{-}heating}$ and thermal energy losses in DHW circulation loop $Q_{W,dis,non\text{-}heating}$ for full non-heating season is calculated as linear interpolation from the relevant data from months with non-heating according to the following formulas:

$$Q_{W,non-heating} = Q_{W,non-heating.count} \frac{t_{non-heating}}{t_{non-heating.count}} \ , \tag{2.2}$$

$$Q_{W,dis,non-heating} = Q_{W,dis,non-heating.count} \frac{t_{non-heating}}{t_{non-heating.count}} \ . \tag{2.3}$$

5. The difference of the DHW temperature ($\theta_{w,o}$) and inlet cold water temperature during heating ($\theta_{w,del,\ heating}$ ) and non-heating season ($\theta_{w,del,non\text{-}heating}$) should be taken into account to calculate the energy for DHW needs during heating season $Q_{w,heating}$ according to the formula

$$Q_{W,heating} = Q_{W,non-heating.count} \frac{t_{heating}}{t_{non-heating.count}} \cdot \frac{(\theta_{W,o}-\theta_{w,del,heating})}{(\theta_{W,o}-\theta_{w,del,non-heating})}. \tag{2. 4}$$

6. The thermal losses of the DHW circulation loop $Q_{W,del,heating}$ depend on the temperature of the DHW in pipe sections $i$ ($\Theta_{w,dis,avg,i}$) and the ambient temperature around the relevant DHW pipe sections $i$ ($\Theta_{amb,i}$) during heating and non-heating seasons. Usually the temperature of the DHW in pipes have a fixed value during heating and non-heating season. The average temperature around the pipes of sections in heated area of the building have equal value during heating and non-heating season, but the difference is caused by the pipes outside the heated areas, i.e. in non-heated basements and attics.

$$Q_{W,del,heating} = Q_{W,dis,non-heating.count} \frac{t_{heating}}{t_{non-heating.count}} \cdot \frac{\Sigma_i \Psi_{W,i} \cdot L_{W,i} \cdot (\theta_{W,cirk,i}-\theta_{amb,i,heating})}{\Sigma_i \Psi_{W,i} \cdot L_{W,i} \cdot (\theta_{W,cirk,i}-\theta_{amb,i,non-heating})} \tag{2. 5}$$

The calculations of the thermal losses of the DHW circulation loops for the investigated buildings show that the difference of ambient temperature during heating and non-heating season for the pipes outside the heating area affect the total circulation losses from 2 % for twelve-storey buildings, to 5 % for five-storey buildings. This conclusion allows us to simplify the formula by substituting the multiplier with differences of ambient temperatures with empiric coefficient K (with the values from 1.02 to 1.05).

$$Q_{W,del,heating} = Q_{W,non-heating.count} \frac{t_{heating}}{t_{non-heating.count}} \cdot K \qquad (2.6)$$

The calculations according to the described method give accurate energy performance indicators of the DHW system and provide the basis for evaluation of the benefits of possible measures for the DHW system of the building.

In order to improve energy performance of the DHW system during energy audit of the building, implementation of the following measures should be considered:

- optimisation of operational settings by setting up the day and night mode conditions, which include switching off during the night hours (for certain types of buildings switching off is possible also during holidays/weekends), the reduction of the temperature of DHW during the night hours;
- replacement of metal (steel or copper) pipes with the pipes with lower thermal conductivity;
- thermal insulation of the distribution pipes (effective for all uninsulated pipes);
- optimisation of distribution network of the circulation pipes, for example, replacement of all or part of distribution pipes with one well-insulated central pipeline with larger diameter;
- installation of the hydraulic flow controllers (thermostatic, self-acting, proportional valves) on each section of the DHW circulation loop to ensure a balanced flow;
- replacement of the fixed power pump with demand controlled variable-speed pump that automatically adjusts to the hydraulic power needs and temperature settings;
- installation of the waste water heat recovery system can be cost effective for the buildings with significant DHW consumption.

# 3. Economic assessment of DHW system heat loss

The thermal losses of the DHW distribution circulation pipe system of the building consists of thermal losses in the basement pipes during the whole year, and thermal losses in the vertical distribution loop pipes during non-heating seasons. The thermal losses from the towel rails of the DHW distribution system give comfort in bathrooms and may be useful throughout the whole year. As concluded in Section 1.5, characteristic thermal losses from the DHW circulation loop are on average 20 kWh/m$^2$/yearly for the apartment buildings of standard design with originally installed DHW system steel pipes.

For a standard design apartment building with total area of 4000 m$^2$ and typical thermal losses of the DHW systems (20 kWh/m$^2$/per year) the total thermal losses of the DHW systems are 80 MWh yearly and the costs for the apartment owners are €4062 ([2]). After insulation (10 to 20 mm thickness with a thermal conduction of 0.04 W/(m$^2$·K)) of the DHW pipes the linear thermal characteristic value of pipes ranges from 0.1 to 0.2 W/(m·K) or less. Such activities reduce thermal losses from the DHW system by 70 % or about 14 kWh/m$^2$/per year therefore yearly savings are 56 MWh of heat energy and of costs − € 2843.

According to the data of "Rīgas siltums" Ltd. about 4000 apartment buildings with total heating area of 12 million m$^2$ connected to district heating network in Riga use heat energy for heating and DHW needs. Most of these buildings and their heating and DHW systems have not been improved since the construction of buildings. The assessed thermal losses of DHW systems of these buildings are 240 GWh per year that costs € 12.2 million annually to apartment owners. The insulation of distribution pipes of the DHW systems of these buildings can save 168 GWh of heat energy and € 8.5 million of costs annually.

# Conclusions

1. The doctoral thesis found that tere are two components of energy consumption of the DHW system in apartment buildings − heat for DHW needs and heat loss in the DHW circulation loop, which do not have a linear relationship with each other. At the same time, the study confirms that energy consumption of the DHW system in apartment building has two distinctly independent correlative relationships indicated by the following values of determination coefficient: 1) consumed volume of DHW and the required energy depend on the number of inhabitants ($R^2 = 0.94$), dwelling area ($R^2 = 0.84$–$0.93$), and the number of apartments ($R^2 = 0.81$–$0.88$); 2) the thermal losses of DHW system circulation loop depend on the heated areas of dwellings ($R^2 = 0.91$–$0.92$), number of apartments ($R^2 = 0.86$–$0.88$), and number of circulation loop sections in dwellings ($R^2 = 0.82$–$0.91$).

2. The typical characteristics of DHW consumption of apartment buildings range from 24 to 60 (41 on average) litres per inhabitant per day and are lower than specified in the Latvian Construction Regulation LBN 221-15 (from 85 to 105 litres per inhabitant per day), and from 40.0 to 142.6 litres per day per household (dwelling) on average 91.4. litres for the buildings in

[2] JSC "Rīgas Siltums" heat energy price was 45 € per MWh in 2018 (www.sprk.gov.lv), 12 % VAT rate for heat energy for housing, bruto price of heat energy was 50.77 € per MWh.

Riga and 71.5 litres for the buildings in Bauska, wich is lower than specified in standard EN 15316-3-1 (from 100.2 to 199.8 litres per day per household). Therefore, it is recommended to review the values of DHW consumption specified in the Latvian Construction Regulation LBN 221-15 and the appropriate national annexes of standard EN 15316-3-1 should be developed with DHW consumption characteristics suitable for Latvian conditions.

3. Heat energy losses in the DHW circulation loop can be calculated most accurately based on actual measured data of heat and hot water consumption. By comparison, the calculation gives significantly incorrect result if the standard values and formulas given in standard EN 15316-3-2 and its Annex D (length of pipes, linear heat transfer coefficients of pipes, average temperature of hot water) are used. The most significant error (an average of 400 %) is caused by the inappropriate standard default values of linear thermal transmittance of pipe sections. Furthermore, the length of different pipe sections of DHW circulation loop calculated according to standard formulas also differ from the actual range from 50 % to 320 %.

Considering the inadequacy of the standard values and formulas given in Annex D of standard EN 15316-3-2 for the assessment of the heat energy losses of DHW distribution system, the author of the Doctoral Thesis proposes a calculation model with specified standard values and formulas appropriate for Latvian conditions. Comparison of the actual measured data for various types of standard design buildings and the calculation by the authors model gave the results that differed from 1% to 88 % (43 % on average), which is significantly more accurate than by the standard default model.

4. An assessment of energy performance standards shows that the standards do not describe the methods to assess the energy performance of DHW systems in buildings with a single heat metering for heating and DHW.

The Doctoral Thesis provides a correct calculation method to estimate the energy consumption for DHW needs and heat loss in the DHW circulation loop during heating and non-heating periods. The proposed method takes into account monthly metered data of consumption of heat energy and consumption of hot water volumes in the building, defines the length of heating and non-heating periods, the default values for hot water temperature, the cold water supply temperature during the heating period and non-heating period, and the temperature around the pipe sections.

5. Thermal energy losses of DHW circulation loop vary from 0.1 to 0.28 MWh per month per dwelling for different types of standard design buildings, on average it is 0.18 MWh per month for the buildings in Riga and 0.21 MWh per month for the buildings in Bauska. The study shows that actual thermal energy losses of DHW circulation loop significantly exceed

0.1 MWh – the value recommended by the Riga City Council for one dwelling per month (24 August 2010, Instruction No. 9).

6. The assessment of heat losses of the DHW circulation loop shows that non-recoverable energy losses of DHW circulation loop range from 16 to 24 and on average 20 kWh per $m^2$ per year for the investigated apartment buildings. The result is representative with considerations that non-recoverable energy losses are in the basement during the whole year, in vertical distribution pipes during non-heating season, but heat energy losses from towel rails are useful (not losses) during the whole year.

Economic evaluation of the rebuilding and new insulation of DHW pipeline system indicate that the heat loss in the DHW system circulation loop can be reduced by 70 percent or by 14 kWh/ $m^2$ per year and the rebuilding measures are cost-effective and pay off in less than 10 years.

7. The assessment of the auxiliary energy of the DHW system of the building by different European standard methods (simplified and detailed) gives similar results. The calculation according to simplified method shows that auxiliary energy of the DHW system ranges from 1.1 to 1.9 (1.5 on average) kWh/$m^2$/per year for different types of standard design buildings, while the calculation according to the detailed method gives results ranging from 1.5 to 1.8 (1.6 on average) kWh/$m^2$/per year. The author considers the detailed calculation method to be too complicated and time consuming. Therefore, the simplified method is recommended for use for energy performance certification of buildings. As an alternative, the default value (for example, 2.0 kWh/$m^2$/per year) may be adopted at national level.

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# 4. List of publications

The results of the Doctoral Theses are reflected in 9 scientific publications.

1. Grasmanis, Dz., Sovetnikov, D.O., Baranova, D.V., Energy performance of domestic hot water systems. Magazine of Civil Engineering., St. Petersburg, 2017, No. 8, pp. 140–155, doi: 10.18720/MCE.76.13.
2. Grasmanis, Dz., Talcis, N., Greķis, A., Heat Consumption Assessment of the Domestic Hot Water Systems in the Apartment Buildings, Proceedings of REHVA Annual Conference 2015, Riga, 2015, pp. 167−176, ISBN 978-9934-10-685-9.
3. Grasmanis, Dz., Talcis, N., Greķis, A., Heat Consumption Assessment of the Domestic Hot Water Systems in the Apartment Buildings, Scientific Journal of Riga Technical University – Construction Science, Riga, 2013, pp. 38−43, ISSN 14077329.
4. Grasmanis, Dz., Talcis, N., Greķis, A., Heat Consumption Assessment of the Domestic Hot Water Systems in the Apartment Buildings, Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and the 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni, Latvia, Riga, 2012, p. 414, ISBN 978-9934-10-360-5.
5. Grasmanis, Dz., Energoefektivitātes rādītāju novērtējums ēku sadzīves karstā ūdens sistēmām, REA Vēstnesis, Nr. 34, Rīga, 2017., 5.−14. lpp.
6. Grasmanis, Dz., EPBD implementation in Latvia, Status at end of 2012, in: 'Book of National Reports 2012', 2013, Porto, pp. 237−246, ISBN 978-972-8646-27-1
7. Grasmanis, Dz., Mālnieks, A., Jēkabsons, A. Implementation of the EPBD in Latvia, Status in November 2010, in: 'Implementation of the Energy Performance of Building Directive (EPBD), Featuring Country Reports 2010', Brussels, 2011, III: pp. 223−234.
8. Grasmanis, Dz., Lemšs, I., Nikolajevs, A., Implementation of the EPBD in Latvia: Status and planning - July 2008, in: 'Implementation of the Energy Performance of Building Directive, Country Reports 2008', Brussels, 2008, pp. 120−124.
9. Grasmanis Dz., 9.5. Ēku energoefektivitātes normatīvais regulējums, no: 'Būvniecības vadības rokasgrāmata', 2016-04, Dienas Bizness Rokasgrāmatu daļa, 2016, 44 lpp.

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Grasmanis has participated in elaboration of legal acts and policy documents on energy performance of buildings and construction administration for more than fifteen years. He is a co-author of the method of calculation of the energy performance of buildings specified in Latvian legislation. From 2006 to 2013, he represented the Ministry of Economics acting as Latvian National Coordinator in an ambitious European Union project Concerted Action of Energy Performance of Building Directive (CA EPBD). Grasmanis has experience and knowledge on building administration and energy performance legislation, standards and technologies in many EU countries.

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