The influence of heat loss from pipes in an unheated basement on the heating energy consumption of an entire typical apartment building

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Abstract. The majority of old apartment buildings were designed with an unheated basement. Building service systems such as district heating heat exchangers and pipes for domestic hot water and for space heating are usually located in this unheated basement. In addition, these locations are connected with shafts. All these pipe's heat losses increase air temperature in the basement. If these losses are included into the building energy balance, then they decrease heat loss through the basement ceiling. The basement's heat balance is also dependent on heat loss from the basement envelope and outdoor air exchange in the basement. In early stages of design, designers and energy auditors need rough models to make decisions in limited information conditions. Once the effects of heat losses from pipes become apparent, they need to be factored into the buildings energy balance, and their effects on heat loss through the basement ceiling needs to be calculated. In this paper we analyse the effect these heat losses have on the service system's heat gains and heat loss through an uninsulated basement ceiling at different basement insulation levels and with different thicknesses of pipe insulation. From our study we found that pipe losses in the basement increase the building energy performance value by at least 4 kWh/(m²·a) and their impact on a renovated apartment building is very important.

1   Introduction

Improving the energy performance of buildings is a tool to meet the long-term energy saving and decarbonisation goals of the European Union. In the EU, residential buildings accounted for 27% of energy use and the main use of this energy (64%) by households is for heating their homes [1]. The net energy need for space depends quite linearly on the specific heat loss of the building envelope [2] therefore thermal improvement of the building envelope is one of the most needed renovation measures for old apartment buildings in cold climates [3–5].

Deep energy renovation reduces ca 70% of delivered energy need and ca 60% of primary energy need [6]. Unfortunately, the calculated energy saving is often much more optimistic than the measured savings show [7–10]. The behaviour of occupants has been identified as one of the main causes for difference between predicted and real energy use [11,12]. Nevertheless, construction quality [13,14] and calculation or measurement methods [15,16] also influence the predicted and real energy use.

The majority of old apartment buildings in Estonia were designed and constructed with an unheated cellar or basement. Temperature in the basement depends on heat loss from the building envelope of the basement, heat gains from the first floor and heat loss from the service systems. As lower temperatures prevail in unheated basements, thermal separation of the basement from the heated part of the building is necessary but because of low ceiling height of basements, in most cases it is complicated.

In the detailed design stage, heat loss calculations through the basement ceiling are modelled by software or calculated by standard EN ISO 13370 [17]. In the early stage of design, designers and energy auditors need rough models to make decisions in limited information conditions.

Once the effects of heat losses from pipes become apparent, they need to be factored into the buildings energy balance, and their effects on heat loss through the basement ceiling needs to be calculated. In this paper we analyse the effect these have service system's pipes heat gains and heat loss through an uninsulated basement ceiling at different basement insulation levels: basement walls are well insulated, partly insulated or uninsulated and at different insulation levels of the service systems.

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2 Methods

2.1 Reference building

Our analysis is based on the reference building which represents the most built common apartment building type from 1960-90's (see Fig 1.). The building is a 5-story large concrete panel apartment building with a total heated area 3562 m², constructed in 1986.

Because of serious thermal bridges in these type of non-renovated buildings [13], mould growth was present on interior surfaces, especially in the corners of exterior walls and roof before renovation, and the thermal transmittance of the external envelope was $U = 0.9$–1.1 W/(m²·K). The energy need for heating and domestic hot water was close to 300 kWh/(m²·a). The building had insufficient ventilation, it was subject to overheating during winter and provided unsatisfactory thermal comfort. The reference building was renovated in 2017 according to nZEB criteria (class A, EPV ≤100 kWh/(m²·a)) by means of prefabricated timber frame wall and roof insulation elements [18–20].


Fig 1. Overview of the reference building in 2015 before (above) and in winter 2017 after (below) the nZEB renovation.

2.2 Heat balance model

Heat balance in a basement depends on heat flow through the basement envelopes (Fig. 2) and air exchange. On the other hand, a basement gets heat from apartments (heat flow through basement ceiling (U_r)), and heat gain from

the sun through basement windows. During the 1980's, the typical basement ceiling (U_r) thermal transmittance was, on average, 1.4 W/(m²·K). Typical construction was a concrete floor insulated with 26 mm cellulose plates, overlaid with 20 mm chipboard plates with a parquet covering.
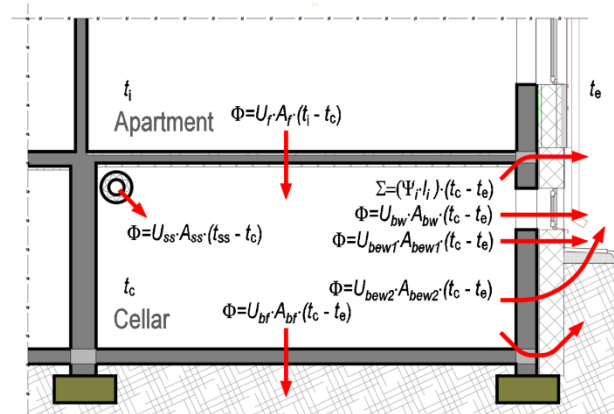
Fig 2 Heat balance of basement of an apartment building.

2.3 Simulations

The indoor climate and energy performance was simulated using the energy and indoor climate simulation program IDA Indoor Climate and Energy [21,22]. This software allows the modelling of a multi-zone building, internal heat gains and external solar loads, outdoor climate, heating and ventilation systems, dynamic simulation of heat transfer and air flows. This software is validated [23–25], and the building model is calibrated against field measurements [26].

The energy performance of buildings is assessed based on primary energy use, expressed by the energy performance value EPV (kWh/(m²·a)) of a whole building (i.e. heating, cooling, ventilation, DHW, lighting, HVAC auxiliary, appliances) according to Estonian legislation [27,28]. The following energy performance criterions were used where the weighting factor for district heating is 0.9 and for electricity is 2.0:

- nZEB renovation, EPV ≤105 kWh/(m²·a) (class A):
  - $U_{bew1} = 0.13$ W/(m²·K) (250 mm of insulation),
  - $U_{bew2} = 0.08$ W/(m²·K) (250 mm of insulation),
  - $U_{bf} = 0.36$ W/(m²·K) (0 mm of insulation),
  - $U_w = 1.0$ W/(m²·K) (triple glazing),

nZEB renovated buildings should have also local energy production, without production EPV should be ≤105 kWh/(m²·a).

- Low energy building renovation, EPV≤150 kWh/(m²·a) (class C),
  - $U_{bew1} = 0.17$ W/(m²·K) (200 mm of insulation),
  - $U_{bew2} = 0.20$ W/(m²·K) (150 mm of insulation),
  - $U_{bf} = 0.38$ W/(m²·K) (0 mm of insulation),
  - $U_w = 1.0$ W/(m²·K) (triple glazing),
- Renovation as usual (2015-2019), EPV≤180 kWh/(m²·a) (class D),
  - $U_{bew1} = 0.22$ W/(m²·K) (150 mm of insulation),
  - $U_{bew2} = 0.39$ W/(m²·K) (100 mm of insulation),
  - $U_{bf} = 0.39$ W/(m²·K) (0 mm of insulation),

- U_w = 1.2 W/(m²·K) (double glazing half changed with triple glazed windows),
- Renovation as usual before 2014, EPV≤220 kWh/(m²·a) (class E),
  - U_{bew1} = 0.22 W/(m²·K) (150 mm of insulation),
  - U_{bew2} = 0.61 W/(m²·K) (0 mm of insulation),
  - U_{bf} = 0.39 W/(m²·K) (0 mm of insulation),
  - U_w = 1.2 W/(m²·K) (double glazing, half changed with triple glazed windows),
- not renovated, EPV ≤280 kWh/(m²·a) (class F),
  - U_{bew1} = 1.0 W/(m²·K) (0 mm of insulation),
  - U_{bew2} = 0.61 W/(m²·K) (0 mm of insulation),
  - U_{bf} = 0.39 W/(m²·K) (0 mm of insulation),
  - U_w= 1.7 W/(m²·K) (2-pane glazing mainly changed between 2000-2010).

In all simulations the air changes in the basement were 0.15 l/(s· m²). In the figures, EPV classes by class symbols (A, C, D, E and F).

2.4 Service system pipes

For thermal insulation of service systems, being domestic hot water pipes (DHW), DHW circulation pipes (Circ.) and heating pipes in the basement, we use the following levels:

- Well insulated pipes (40 mm thermal insulation)
- Average insulated pipes (20 mm thermal insulation)
- No extra thermal isolation

Pipe length of heating distribution pipes (equation 1), DHW (equation 2) and Circ. (equation 3) in the basement are calculated with standard EN-15316-3 [29]. In equations L_L is length and L_W is width of the building.

$$2 \cdot L_L + 0.01625 \cdot L_L \cdot L_w{}^2 \ , (\text{m}) \qquad (1)$$

$$L_L + 0.0625 \cdot L_L \cdot L_w \ \ , (\text{m}) \qquad (2)$$

$$2 \cdot L_L + 0.0125 \cdot L_L \cdot L_w \ \ , (\text{m}) \qquad (3)$$

Outer diameter of pipes in the basement in all simulations:

- DHW   40 mm
- Circ.   20 mm
- Heating pipes   25 mm

Pipes linear thermal transmittances is also calculated by standard EN 15316-3 (4).

$$\Psi \ = \ \frac{\pi}{\frac{1}{2 \cdot \lambda_p} \cdot \ln \frac{d_i}{d_p} + \frac{1}{2 \cdot \lambda_D} \cdot \ln \frac{d_a}{d_i} + \frac{1}{h_a \cdot d_a}} \ \ , \text{W}/(\text{m} \cdot \text{K}) \quad (4)$$

Thermal transmittances from service system pipes are shown in Table 1.

Table 1. Pipes linear thermal transmittances.

Thermal isolation	DHW	Circ.	Heating
mm	Ψ (W/m·K)		
40	0.22	0.16	0.17
20	0.33	0.21	0.24
0	1.22	0.62	0.77

We decided to use a slightly different approach compared to standard EN 15316-3 [29]:

- In our simulations we use a basement temperature as shown in our basic simulations.

When our assumed heat gain to the room from pipes differed by more than 0.1 W/m² (calculated using average temperature from November until March) we made a fresh calculation.

- In our case study building, the length of heating pipes are 77 meter longer than calculations showed but we decided to use length which is calculated by standard
- We focused only on pipe heat losses in an unheated basement.

Pipe losses in shafts and apartments are not calculated.

- Pipes linear thermal transmittances are calculated as reference building average pipe sizes after nZEB renovation.

To compare results, we used the same pipe sizes in all simulation cases.

3 Results

3.1 Service system pipe length and heat loss

Heat loss through pipes depends on the pipes inner flow temperature and also the outside temperature. In all simulations we used an inner flow temperature for DHW of 55ºC, Circ. 52ºC and Heating 40ºC (from 15 of April until 15 of October 30 ºC) . Basement temperature depends on the balance of heat losses and heat gains in the basement. In our basic simulation we attempted to provide for this by making the calculations without pipe heat losses and then assuming a figure for pipe heat loss with which to adjust the final temperature calculation. This was clearly not a preferred approach and our solution was to make detailed model for this.

Pipes length in basement by standard EN-15316-3:
- DHW   112 m
- Circ.   126 m
- Heating pipes   329 m

Compared to the reference building, DHW pipes are 5 m longer in length, Circulation pipes 19 m longer and Heating pipes 77 m shorter. Which means that heat losses in the reference building are, with the same thermal insulation, greater.

From the length and thermal transmittance of the pipes, the pipes inner temperature and the estimated

basement temperature we calculate the pipes heat losses to the basement (Table 2).

Table 2. Pipe heat losses in basement in different simulation cases.

| Simulation model according to buildings energy performance certificate	Pipes insulation in basement	Pipe heat loss to basement in heating period
	mm	W/m²
A	no heat loss from pipes	0
	40	4.0
	20	5.4
	0	14.4
C	no heat loss from pipes	0
	40	4.0
	20	5.5
	0	15.0
D	no heat loss from pipes	0
	40	4.1
	20	5.7
	0	15.5
E	no heat loss from pipes	0
	40	4.1
	20	5.6
	0	15.4
F	no heat loss from pipes	0
	40	4.1
	20	5.8
	0	15.5

From 15 of April until 15 of October pipe heat losses are 70% of heating season losses. Recalculations with simulated temperature outside of heating season showed that in all cases it is between 65% until 70% which mean this assumption is more or less the same.

3.2 Influence of pipe heat loss on temperature in the basement and heat flow through the basement's ceiling

Our calculations with different EPV classes for the building with different thickness of thermal insulation on pipes showed that, without involving pipes in the calculations, the average temperature in the basement (between 16 of October until 14 of April) in the base cases is between 11ºC and 12.7ºC. When pipes are not insulated, there could be a basement temperature rise of up to 22.3ºC in cases where the basement envelopes are well insulated. In other cases, the basement temperature without pipe insulation was 20ºC or 21ºC. In cases where pipes are insulated with 20 mm or 40 mm thick insulation we can see in Fig. 3 that the average temperature is between 13.8ºC and 16.3ºC. In this section we can see that when basement envelopes are not insulated, then heat flow through the basement ceiling is more than 8 W/m² which is comparable with the base case basement where there are no pipes and envelopes are well insulated.
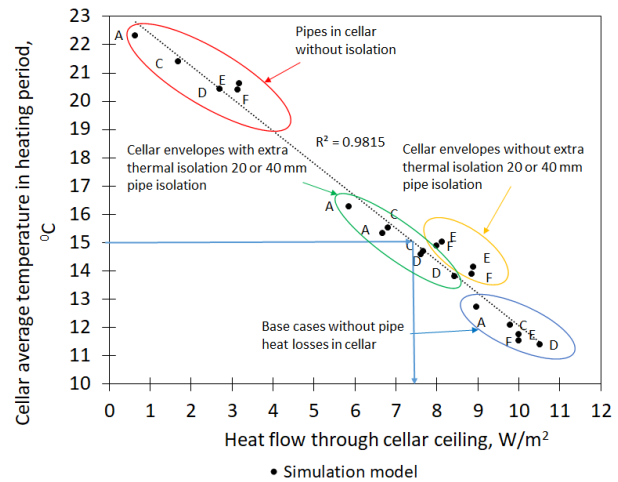
Fig 3. Basement average temperature between 16 of October until 14 of April compared with heat flow from basement ceiling in different simulation cases.
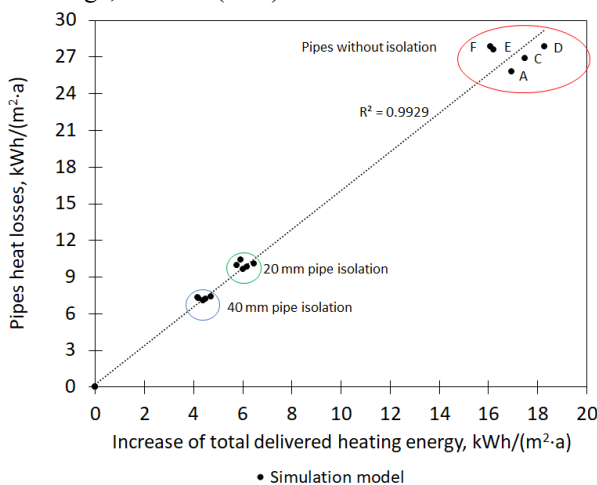
Service system pipes annual heat losses per heated area compared with heat flow through basement ceiling are presented in Figure 4. Here we can see that delivered energy growth is directly connected with pipe insulation. Without thermal insulation, delivered energy is, in all cases, on average 27 kWh/(m²·a) but heat flow through the basement ceiling depends on how well insulated are the basement envelopes. With 20 mm or 40 mm pipe insulation, the pipe losses delivered energy of between 7 to 10.5 kWh/(m²·a), and variation in the ceiling heat flow is the same as cases where pipes are not insulated.
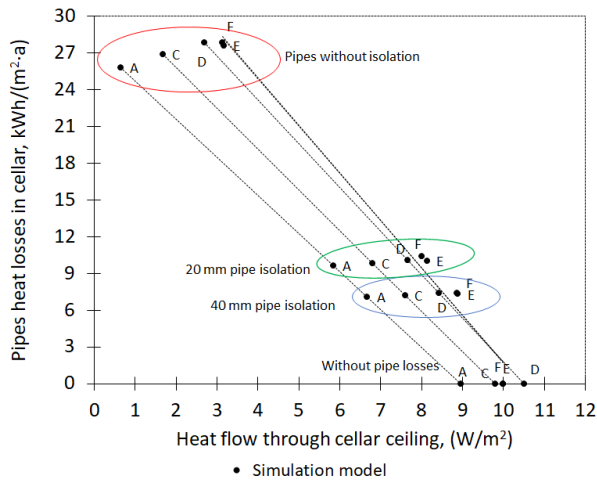
Fig 4. Service system pipes annual heat losses per heated area compared with heat flow through basement ceiling.

### 3.3 The influence of pipes heat loss to delivered heating energy

Fig. 5 shows how the pipes annual heat losses influence the entire building heating energy need. This is caused by a decrease of the basement ceiling energy loss. If the pipes annual heat loss is 7 kWh/(m²·a) than the increase in the entire heating energy is, on average, 4.5 kWh/(m²·a), however, when pipes are not insulated the difference is greater. With a 27 kWh/(m²·a) annual heat loss from the pipes, this increase in entire delivered heating energy is, on average, 17 kWh/(m²·a).

Fig 5. Service system pipes annual heat losses per heated area compared with building total delivered heating energy increase.

From this we can say that 10 kWh/(m²·a) of heating energy is utilised. Looking deeper at all cases, we can say that the average decrease of building total delivered heating and ventilation heat energy is greater when the losses from service system pipes in the basement are greater. In Fig. 6 we show that, in buildings with better envelope insulation, the decrease is lower compared to buildings where the basement envelopes are not insulated,

but the increase in total heating energy is more or less the same with different pipe insulation thicknesses.
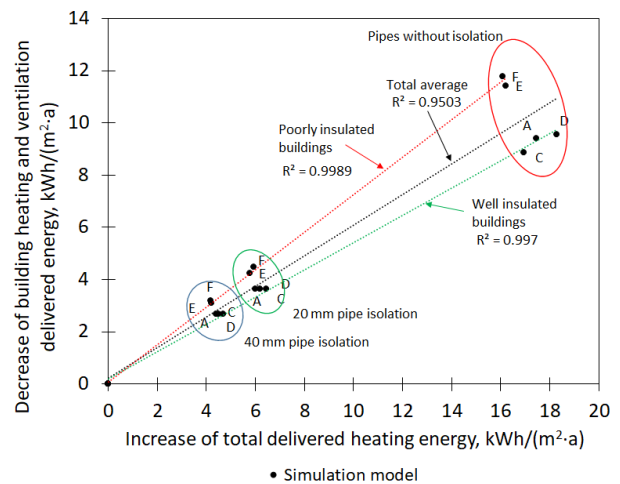
Fig 6. Decrease of building delivered heating and ventilation heat energy compared with building total delivered heating energy increase.

Fig 7. shows the building models total delivered heating energy consumption with basement pipe losses compared to the pipe losses proportional share of this loss. If the building is not renovated, or the building is renovated as EPV class E, then, with insulated pipes, this proportional loss is up to 9% of the entire delivered energy, and with un-insulated pipes, up to 22%. When pipes are insulated and our delivered energy for the entire heating is less than 60 kWh/(m²·a), in line with apartment buildings that are renovated today, then pipe losses can be up to 33% of the entire heating energy losses.
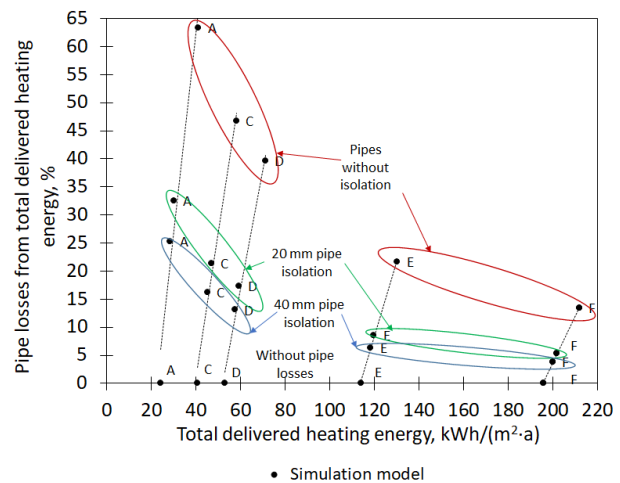

Fig. 7. Building models total delivered heating energy consumption with basement pipe losses compared with pipe losses from total delivered heating energy.

3.4 Energy performance value change and basement temperature

If pipe heat losses with insulated service system pipes is, on average, a 3.8 to 5.8 kWh/(m²·a) increase in total delivered heating energy, then it is also an increase in the total primary energy consumption (EPV). In Fig. 8 we can

see that the increase of primary energy consumption with well insulated pipes is 4 kWh/(m²·a), and with 20 mm insulated pipes averages 5.5 kWh/(m²·a). In existing buildings, this means up to a 2% increase and in nZEB buildings an increase of up to 4.3%.
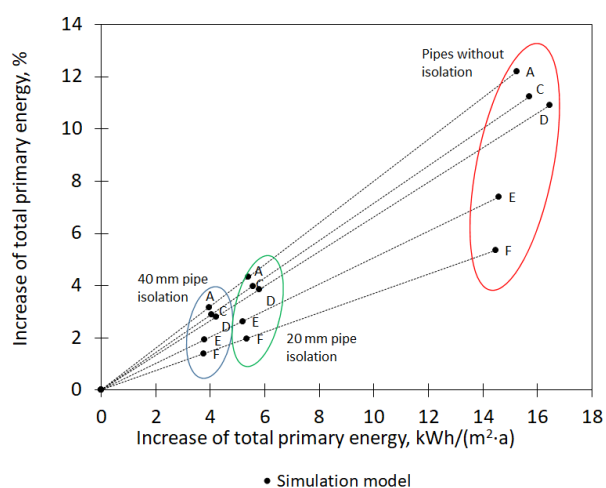
Fig 8. Increase of total primary energy

Comparing primary energy change with average basement temperature (Fig. 9) we can see that in an nZEB building with 20mm pipe insulation, the EPV is 5.3 kWh/(m²·a) greater than our base case and the basement average temperature is 16.2ºC.
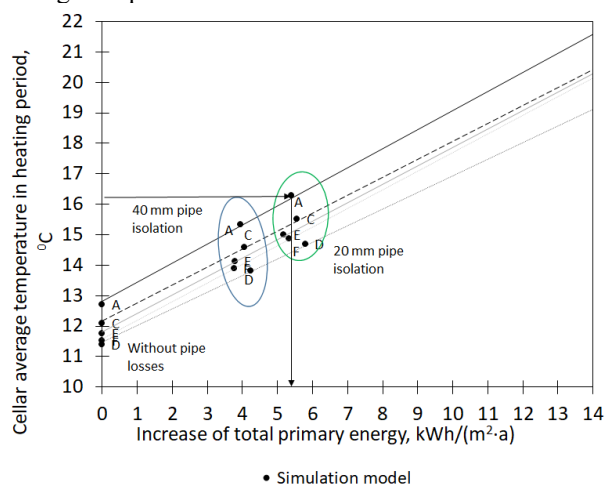
Fig 9. Basement average temperature between 16 of October until 14 of April compared with the increase in total primary energy.

4   Discussion

This study focused on the effect of pipe heat losses on the entire building energy consumption. As typical Estonian apartment buildings have unheated basements, then for energy calculations, we calculated this as an unheated zone without internal heat gains. In existing situations there exist losses from pipes. In the Estonian energy efficiency calculation method [30] we don't calculate pipe losses as a part of the energy performance number. This differs from the German calculation approach. The

German standard for calculating energy efficiency of buildings [31] uses the same calculation method for calculating pipe losses as we used in our case studies. However, the German standard also calculates heat losses from pipes in shafts and in apartments.

The standard EN 15316-3 [29] says that in unheated basements, the temperature used in calculations is 13ºC and our simulations showed that the average temperature between December until the end of February is, on average, more or less the same, but in buildings with good thermal insulation it is higher even if service pipes are well insulated. If pipe insulation is poor, then heat losses from pipes also serve to raise the temperature up to 20ºC. Heat flow through the basement ceiling depends directly on the basement temperature which means that heat losses in the basement can also be partly utilised for decreasing heating energy consumption. Our calculations showed that the potential decrease in delivered energy compared to the potential increase of delivered energy is small and this depends on the thickness of the service pipes thermal insulation and the buildings total delivered heating energy. In buildings where there are large heat losses from the envelope and ventilation, the share of pipe heat losses can be up to 10% which is almost unnoticeable, but in buildings where the energy efficiency goal is to have, after renovation, optimal heating energy consumption, there can be heat losses from pipes that are up to 30% with 20 mm of pipe insulation. From this we can say that service pipe heat losses must be included in energy efficiency calculations.

When pipe losses in an nZEB are 6.6 kWh/(m²·a), then the decrease from ceiling heat losses is 2.2 kWh/(m²·a) which means that the total increase is 4.4 kWh/(m²·a).

Our analyse showed that in buildings with district heating, the EPV number, with 40 mm pipe insulation, is at least 4 kWh/(m²·a) and with 20 mm pipe insulation, 6 kWh/(m²·a). With longer heating pipelines in the basement, the increase of EPV can be even greater.

Our goal was also to provide energy auditors with a graph from which they can easily take average basement pipe heat losses in situations where they have only measured indoor temperature in the basement. For example, when an EPV class "C" building basement average temperature is, during the period December until the end of February, on average, 14ºC, then the EPV component for pipe losses is, in an average renovated apartment building, 5 kWh/(m²·a).

The impact of service pipe losses in basements has been analysed a few times in earlier studies. Most papers on this have been focused on analysing the efficiency of DHW. Bohm [32] show in his study that DHW efficiency is 0.30 up to 0.77 (heat losses are 23% up to 70%) in apartment buildings. In his calculation, most of the losses comes from DHW circulation losses. A large impact from DHW circulations has also been shown in other studies [33–37]. In our study, most of the pipe losses are also involved with DHW system losses. The proportion of DHW losses from the entire pipe loss is approximately 75%.

5 Conclusion

Our study showed that pipe losses in a typical highly insulated Estonian apartment building with an unheated basement and insulated pipes have a large effect on the EPV value. In apartment buildings with district heating, the difference with, and without pipe losses, to the EPV is at least 4 kWh/(m²·a). From the total delivered heating energy consumption in an nZEB building this is 25%. If the total increase coming from pipe losses in the same situation is 7.1 kWh/(m²·a) but the decrease from internal heat gain in the basement is 2.7 kWh/(m²·a), we find a total increase of delivered heating energy of 4.4 kWh/(m²·a). Internal heat gain from pipes means that heat flow from the heated zone through the basement ceiling (Ur=1.4 W/(m²·K)), between December until the end of February, is 6.7 W/m²,and without pipe losses, 9.0 W/m².

The basement average temperature in heating period (16 of October until 14 of April) can also demonstrate just how big the losses from pipes can be, and how this affects the EPV. In existing houses with poorly insulated pipes, the average basement temperature is 16ºC, which means that the EPV can be increased to more than 5 kWh/(m²·a) (Fig. 8).

The results of our analyses are a good base from which to analyse the effect of pipe heat losses in the basement of a typical Estonian apartment building on the building energy efficiency, and our figures can be used to evaluate the impact of pipe losses on its energy efficiency.

References

1. Eurostat, *Energy Consumption in Households* (2019)

2. J. Kurnitski, T. Kalamees, and T. Tark, in *7th Int. Cold Clim. HVAC Conf.* (2012)

3. K. Kuusk and T. Kalamees, Build. Res. Inf. **44**, (2016)

4. T. Niemelä, R. Kosonen, and J. Jokisalo, Sustain. Cities Soc. **32**, 9 (2017)

5. L. La Fleur, P. Rohdin, and B. Moshfegh, Energy Build. **203**, (2019)

6. K. Kuusk and T. Kalamees, Energy Procedia **78**, 985 (2015)

7. A. Hamburg and T. Kalamees, Energy Build. (2019)

8. D. Calì, T. Osterhage, R. Streblow, and D. Müller, Energy Build. **127**, 1146 (2016)

9. S. Cozza, J. Chambers, and M. K. Patel, Energy Policy 111085 (2019)

10. K. Kuusk, T. Kalamees, S. Link, S. Ilomets, and A. Mikola, J. Civ. Eng. Manag. **23**, 67 (2017)

11. A. Hamburg and T. Kalamees, Energies **11**, 3179 (2018)

12. L. La Fleur, B. Moshfegh, and P. Rohdin, Energy Build. **146**, 98 (2017)

13. S. Ilomets, K. Kuusk, L. Paap, E. Arumägi, and T. Kalamees, J. Civ. Eng. Manag. **23**, 96 (2017)

14. L. Evangelisti, C. Guattari, P. Gori, and R. Vollaro, Sustainability **7**, 10388 (2015)

15. K. Kuusk, J. Kurnitski, and T. Kalamees, Energy Procedia **132**, 27 (2017)

16. G. Desogus, S. Mura, and R. Ricciu, Energy Build. **43**, 2613 (2011)

17. EN ISO 13370, *Thermal Performance of Buildings — Heat Transfer via the Ground — Calculation Methods* (Geneva, Switzerland, 2017)

18. P. Pihelo, M. Lelumees, and T. Kalamees, in *Int. RILEM Conf. Mater. Syst. Struct. Civ. Eng. Conf. Segm. Moisture Mater. Struct. 22-24 August 2016, Tech. Univ. Denmark, Lyngby, Denmark* (2016)

19. P. Pihelo, M. Lelumees, and T. Kalamees, in *Energy Procedia* (Proceedings of the SBE16 Tallinn and Helsinki Conference in Energy Procedia; Build Green and Renovate Deep, 5-7 October 2016, Tallinn and Helsinki., 2016), pp. 745–755

20. P. Pihelo, T. Kalamees, and K. Kuusk, in *Proc. 3rd Int. Conf. Innov. Mater. Struct. Technol. IMST2017,* (IOP Publishing Ltd, 27-29.09.2017, Riga, Latvia, 2017)

21. P. Shalin, Modelling and Simulation Methods for Modular Continuous System in Buildings, KTH, Stockholm, Sweden, 1996

22. N. Björsell, A. Bring, L. Eriksson, P. Grozman, M. Lindgren, P. Sahlin, A. Shapovalov, B. Data, and M. Vuolle, in *Proc. IBPSA Build. Simul. '99 Conf.* (Kyoto, Japan, 1999), pp. 1–8

23. S. Moinard and G. Guyon, *Empirical Validation of EDF ETNA and GENEC Test-Cell Models A Report of Task 22 Building Energy Analysis Tools* (1999)

24. J. Travesi, G. Maxwell, C. Klaassen, and M. Holtz, *Empirical Validation of Iowa Energy Resource Station Building Energy Analysis Simulation Models, IEA Task 22, Subtask A* (2001)

25. M. Achermann and G. Zweifel, *RADTEST – Radiant Heating and Cooling Test Cases, Subtask C. A Report of IEA Task 22. Building Energy Analysis Tools.* (2003)

26. A. Hamburg, K. Kuusk, A. Mikola, and T. Kalamees, Energy 116874 (2019)

27. 14 RT I, 13.12.2018, *Decree of the Minister of Entrepreneurship and Information Technology Nr 63 (11.12.2018). Energy Performance Requirements of the Buildings (in Estonian:*

Ettevõtlus- Ja Infotehnoloogiaministri Määrus Nr 63 (11.12.2018). Hoone Energiatõhususe Miinimumnõuded (Riigi Teataja, 2018)

28. 13 RT I, 18.01.2019, *Decree of the Minister of Economic Affairs and Infrastructure Nr 36, (Redaction 21.01.2019). Requirements for Energy Label Issuing and Energy Labeling (in Estonian: Majandus- Ja Taristuministri Määrus Nr 36 (Redaktsioon 21.01.2019). Nõuded Energiamärgise* (Riigi Teataja, 2019)

29. EN 15316-3, *Energy Performance of Buildings - Method for Calculation of System Energy Requirements and System Efficiencies - Part 3: Space Distribution Systems (DHW, Heating and Cooling), Module M3-6, M4-6, M8-6* (Brussels, 2017)

30. 7 RT I, 19.01.2018, *MKM Määrus Nr. 58, Hoonete Energiatõhususe Arvutamise Metoodika (Minister of Economic Affairs and Communications Regulation Nr. 58, Methodology for Calculating the Energy Performance of Buildings)* (2018)

31. DIN V 18599, *Energetische Bewertung von Gebäuden - Berechnung Des Nutz-, End- Und Primärenergiebedarfs Für Heizung, Kühlung, Lüftung, Trinkwarmwasser Und Beleuchtung (Energy Efficiency of Buildings - Calculation of the Net, Final and Primary Energy Demand* (2018)

32. B. Bøhm, Energy Convers. Manag. **67**, 152 (2013)

33. T. Cholewa, A. Siuta-Olcha, and R. Anasiewicz, J. Clean. Prod. **217**, 194 (2019)

34. Y. Zhang, C. Bonneville, S. Wilson, M. Maroney, J. Staller, and J. Yun Wei, ASHRAE Trans. **118**, 357 (2012)

35. A. Marszal-Pomianowska, C. Zhang, M. Pomianowski, P. Heiselberg, K. Gram-Hanssen, and A. Rhiger Hansen, Energy Build. **184**, 53 (2019)

36. J. E. Thorsen and T. S. Ommen, in *16th Int. Symp. Dist. Heat. Cool. DHC2018* (9–12 September 2018, Hamburg, Germany, 2018), pp. 197–205

37. K. Zvaigznitis, C. Rochas, G. Zogla, and A. Kamenders, Energy Procedia **72**, 245 (2015)