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Energy Performance, Indoor Air Quality And Comfort in New Nearly Zero Energy Day-Care Centres in Northern Climatic Conditions

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Energy Performance, Indoor Air Quality and Comfort in New Nearly Zero Energy Day-care Centres in Northern Climatic Conditions

Kalle Kuusk
Tallinn University of Technology, Estonia

Ahmed Kaiser
Aalto University, Finland

Nicola Lolli
SINTEF, Norway

Jan Johansson
Växjö Kommun, Sweden

Tero Hasu
Kouvola Innovation Ltd., Finland

Anne Gunnarshaug Lien
SINTEF, Norway

Endrik Arumägi, Kristo Kalbe, Jaanus Hallik
Tallinn University of Technology, Estonia

Jarek Kurnitski
Aalto University, Finland

Targo Kalamees*
Tallinn University of Technology, Estonia

*Corresponding author: **targo.kalamees@taltech.ee**

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The European energy policy pushes the member states to transform building stock into nearly Zero-Energy Buildings (nZEB). This paper is focused on data collected from existing nZEB day-care centres, in order to be able to assess possible differences between predicted and actual energy and indoor environmental performance. Building structures, service systems and the indoor climate and energy performance of five day-care centres were investigated in Estonia, Finland and Norway.

Indoor climate condition measurements showed that in general, the thermal environment and indoor air quality corresponded to the highest indoor climate categories I and II (EN 15251). Building heating and ventilation systems in studied buildings are working without major problems. Good indoor climate conditions

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were also reflected in the occupant satisfaction questionnaires. For most of the studied buildings, over 80% of the people marked all indoor environment condition parameters (thermal comfort, indoor air quality, acoustics, odour and illuminance) acceptable. The thermal environment in the cooling season was reported problematic because it was lower than the minimum temperature for indoor climate category II.

Energy consumption analysis showed that measured real energy use was higher, or even significantly higher, than the energy use calculated during the design phase. Potential causes of the higher actual energy consumption are caused by differences of measured and designed solutions, methodology of the energy calculations, and the differences in user behaviour.

Lessons learnt from previously constructed day-care centres can be utilised in the planning and design of new nZEBs.

Keywords: indoor thermal conditions, indoor air quality, occupant satisfaction, energy consumption, nZEB, day-care centres.

Introduction

By the end of 2020 (2018) for buildings occupied and owned by public authorities), all new buildings should comply with the Energy Performance of Buildings Directive (EPBD, 2010) obligations. Many member states (MS) have already shifted minimum requirements to the cost optimal level. Kurnitski et al., (2018)as the latter was needed for comparing with the national NZEB requirements. In this comparison, various technical solutions were selected so that the building complied with EC recommendations. Then the technical solutions were adjusted to achieve the closest compliance with the national NZEB requirements in the four selected EU countries. The technical solutions showing the highest energy performance highlighted the strictest national NZEB requirements. Energy performance with national NZEB solutions was benchmarked against the EC recommendation by using input data representing a standard use and applying the ISO 52000-1:2017 primary energy factors (PEF showed that the direct comparison of the building energy performance between the EC recommendation and the national nZEB primary energy values produced inconsistent results because of the variation of both the primary energy factors and the energy calculation input data in national regulations. This complicates free movement of goods and services and overall export between member states. More information is needed on what kind of building properties are required in different countries to guarantee fulfilment of nZEB requirements.

Fisk (2017) showed, by literature review, that ventilation rates in classrooms often fall far short of the minimum ventilation rates specified in standards. It is important to assure healthy and clean environments to children in day-care centres because wheezing and other breathing related issues in preschool children are common (Grigg and Ducharme, 2019) and more than half of all school children have some kind of allergic condition (asthma, eczema and seasonal allergic rhinitis) (Haanpää et al., 2018). Kolarik et al. (2016) showed a statistically significant inverse relationship between sick-leave and the ventilation air exchange rate in day-care centres. Therefore, it is extremely important that energy savings do not bring about a deterioration of the indoor climate.

It is quite common that the real measured building energy consumption is much higher than the predicted consumption during design (de Wilde, 2014; Desideri et al., 2012). This performance gap hinders the realisation of energy conservation targets. Achieving nearly Zero-Energy Buildings (nZEB) needs multi-attribute assessment (Zavadskas et al., 2017), as in addition to nearly zero or a very low amount of energy required, this required energy should be provided to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

To guarantee nearly zero or a very low amount of energy use, the building envelope and service systems should be very effective. Heat loss of the building envelope depends on thermal transmittance U, W/(m$^2\cdot$K), linear thermal transmittance Ψ, W/(m·K), point thermal transmittance χ, W/K, and airtightness of the building envelope q_{50}, m^3/(hm^2). Bikas and Chastas (2014) showed that in all climatic zones, the reduction of the thermal transmittance leads to a significant reduction in the primary energy consumption by end use, and in the energy requirements for heating. For example, the thermal transmittance of the external walls for nZEB should be 5% of older buildings thermal transmittance in Latvia, 10% in Estonia and up to 50% in Portugal (Kalamees et al., 2016). Ilomets et al., (2017) showed that that thermal bridges contribute more than 30% of the total transmission heat loss, depending on the wall insulation thickness. Levinskyte et al., (2016) showed that when effective solutions for linear thermal bridges are used, the same energy efficiency of the building can be reached using less thermal insulating layers and windows and doors of a lower thermal behaviour, if a building with better energy characteristics is designed. The existing situation of airtightness of the building envelope is often not sufficient (Banionis et al., 2013). Better information about effective energy performance measures helps design and construct buildings with a smaller performance gap.

In addition to operational energy use, embodied energy (Kylili et al., 2016) is also important, as the latest EPBD targets decarbonised building stock by 2050 (EPBD, 2018). Greater use of wood-based materials helps to reduce fossil energy use and to mitigate climate change. The primary energy used and the CO_2 emission resulting from production are lower for wood-framed constructions than for concrete-framed constructions (Gustavsson and Joelsson, 2010).

This paper is focused on data collected from existing nZEB day-care centres, in order to be able to assess possible differences between predicted and actual energy and indoor environmental performance. The main objectives of current study are:

- To determine the technical solutions of modern, energy efficient, and nZEB day-care centres;
- To find out possible differences between predicted and actual energy and indoor environmental performance;
- To map the shortcomings that should be considered when designing future nZEB day-care centres.

Lessons learnt from previously constructed nZEB buildings can be utilised in the planning and design of new nZEBs.

Methods

Studied buildings

The energy use, indoor climate, and building envelope structures were investigated in five day-care centres in three countries, **Table 1**, **Table 2**, and **Fig. 1**. Most of the day-care centres were wooden buildings.

Building description	Estonia 1	Estonia 2	Finland 1	Finland 2	Norway 1
Construction year	2017	2017	2015	2014	2013
Net floor area, m²	1539	1172	1170	1192	950
Mean occupant density,	10 m²/person	12 m²/person	10 m²/person	10 m²/person	14.4 m²/person
Ventilation system	Supply-exhaust air handling units with heat recovery				
Heating system / heat source	Floor and radiator heating /Gas boiler	Floor and radiator heating / GSHP	Floor and radiator heating/Gas boiler	Floor heating / Ground source heat pump (GSHP)	Radiator heating / GSHP
Cooling system / source	None	Cooling coil in ventilation / GSHP	Cooling coil in ventilation / Air heat pump	None	Cooling coil in ventilation / GSHP
On site renewable energy systems	None	PV-panels 17 kW	None	Geothermal heat	Solar collectors 6m²
Designed Energy Performance Certificate (EPC)	C (minimum requirements)	A (nZEB)	C (minimum requirements)	B (low energy building)	NS 3700 (Norwegian PH)
Heating degree days, t_b 17 °C	4220	4220	4392	4392	4302
Vent. airflow rate	1.6 l/(m² s)		2.5 l/(m² s)		2.4 l/(m² s)
Heat recovery efficiency	75 %		67 %	76 %	85 %
Specific fan power	2.0 kW/(m³/s)	≈2.0 kW/(m³/s)	1.85 kW/(m³/s)	1.9 kW/(m³/s)	1.3 kW/(m³/s)

Table 1

Basic information of studied day-care centres

Table 2

Characteristics of building envelope

	Estonia 1	Estonia 2	Finland 1	Finland 2	Norway 1
Thermal transmittance U, W/(m² K)					
Exterior walls	0.19	0.13	0.17	0.15	0.09
Roof	0.10	0.06	0.09	0.08	0.09
Ground floor	0.20	0.09	0.16	0.16	0.08
Doors	1.00	1.10	1.00	1.00	0.80
Windows	1.00	0.85	1.00	0.84	0.80
Window g-value	0.25-0.50	<0.50	0.36	0.36	0.37
Airtightness q_{50}, $m^3/(h{\cdot}m^2)$	3.8*	0.6	2.0	0.36	0.14
Building structures	Timber frame	Concrete elements	Timber frame	Timber frame	Cross laminated timber

* Measured value

Fig. 1

Studied day-care centres

Estonia 1

Estonia 2

Finland 1

Finland 2

Norway 1

Evaluating energy consumption and indoor climate

Energy audits were done for each building to show the energy consumption. The information regarding energy consumption (electricity, space heating together with ventilation air heating (heat) and domestic hot water (DHW)) was measured and data was collected from building managers. Heating energy consumption is normalised to the standard year climate conditions.

To compare the gap between designed and measured energy consumption levels, we have used the following equation (Equation 1):

$$\text{Performance gap} = \frac{100 \times (\text{Measured (M)} - \text{Designed (D)})}{\text{Measured (M)}} \% \qquad (1)$$

Indoor climate conditions were evaluated according to the standard EN-15251 (2007). Indoor environment quality is divided into four categories: I, II, III and IV, Table 3. Category I represents the

Table 3

Indoor temperature range in different climate categories

Indoor climate parameter	🟥 IV	🟨 III	🟩 II	🟩 I
$t_{heating}$, °C	T<19 or T>25	22±3	22±2	22±1
$t_{cooling}$, °C	T<22 or T>27	24.5±2.5	24.5±1.5	24.5±1
CO_2, ppm	>1200	<1200	<900	<750

highest level of expectation and is recommended for spaces occupied by sensitive persons such as the elderly and children. Category II represents normal conditions and should be used as the target for new and renovated buildings. Category III is the minimum an existing building should reach, while Category IV represents IEQ that should be acceptable for only a limited part of the year.

Indoor climate conditions measurements (air temperature, RH, air velocity, CO_2) were conducted across the occupancy period from Monday to Friday during both heating (winter), and cooling (summer) seasons of occupancy. Measurements were conducted in all buildings in at least 2–4 rooms during the heating and cooling periods. The temperature and humidity were measured with portable data loggers. Airflow was measured using the supply and exhaust air airflows.

Indoor climate conditions were also assessed with occupant surveys delivered to employees. The survey included six questions regarding indoor environment quality including; thermal comfort, indoor air quality, acoustics, odour, and illuminance. Thermal comfort, IAQ, illuminance, and acoustics were assessed with a four-point scale from clearly acceptable to clearly unacceptable. Odour was scaled with six possible answers from no odour to overpowering odour. Thermal sensation was also surveyed with six possible answers from hot to cold.

Results

Measurements

Thermal comfort

During the heating season, the room temperature corresponded to indoor climate category I or II criteria 87% - 100% of the time, **Fig. 2**, **Fig. 3**. During the cooling season correspondence to indoor climate category I or II criteria was much smaller: 21% - 54% of time in Estonia, 15% - 37% in Finland, and in Norway 100% of the time. Thermal environment during the cooling season is in

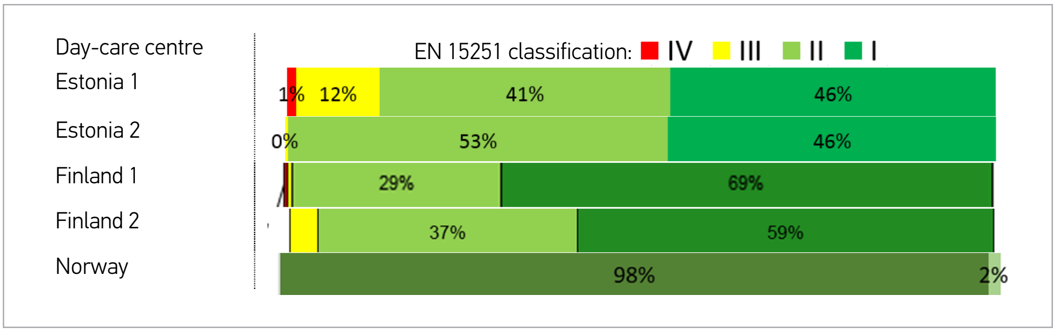

Fig. 2

Thermal comfort results in studied day-care centres during heating season

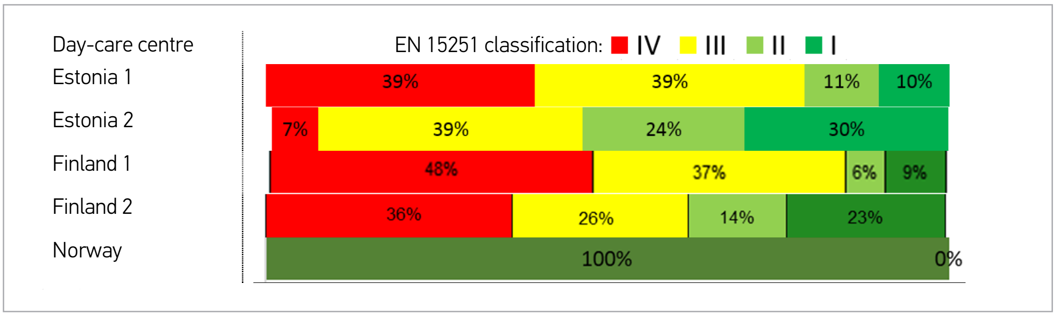

Fig. 3

Thermal comfort results in studied day-care centres during cooling season indoor climate categories III and IV because the measured room temperature was lower than the minimum temperature for indoor climate category II.

Indoor air quality

Indoor air quality was evaluated based on indoor CO_2 concentration measurements during heating (**Fig. 4**) and cooling (**Fig. 5**) seasons. During the heating season, the indoor air quality corresponded to indoor climate category I or II criteria 65 - 99% of time and during the cooling season 64 - 100% of time.

Average CO_2 levels were in the acceptable level, **Table 4**.

Fig. 4

Indoor air quality results during heating season

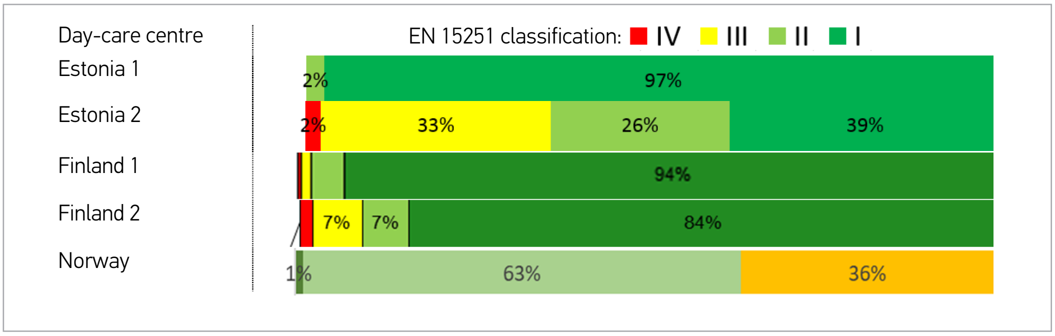

Fig. 5

Indoor air quality results during cooling season

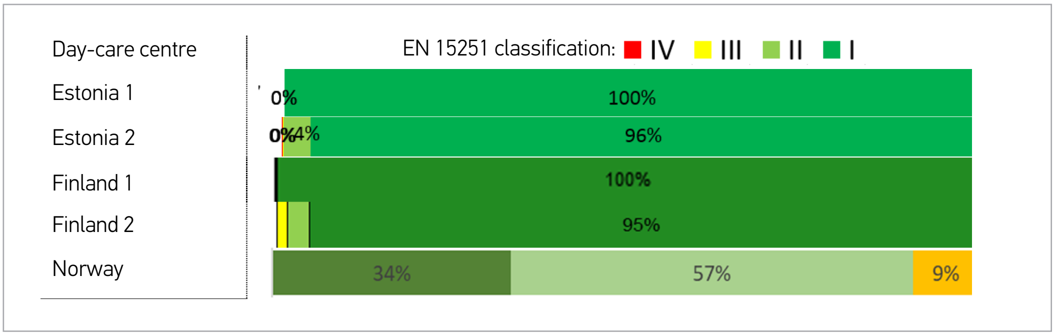

Table 4

Average CO_2 levels and ventilation air flow during occupancy period in studied day-care centres

CO_2 level during occupancy, ppm	Occupant (satisfaction), %				
	Estonia 1	Estonia 1	Finland 1	Finland 2	Norway
Heating season	547	808	501	553	497
Cooling season	516	496	410	424	359

Occupant surveys

The overall indoor environment was very good as occupant satisfaction was 90% or more, **Table 5**.

Table 5

Summary of occupant satisfaction with the indoor climate

	Occupant (satisfaction), %				
	Estonia 1	Estonia 2	Finland 1	Finland 2	Norway
Overall indoor environment	100	100	94	93	90
Thermal environment	100	100	100	82	90
Indoor air quality	100	100	88	100	80
Illuminance level	100	100	100	100	100
Acoustic level	100	100	100	88	91
Odour intensity	100	100	81	94	90

Energy Performance

Table 6 presents annual delivered and primary energy use in the studied day-care centers. Energy use in the Norwegian day-care center was lower than designed. In other day-care centers this was contrariwise. The energy performance certificate was two to four classes lower in the studied buildings, **Fig. 6** left. The performance gap varied between 25 % - 67% and it was larger in more energy efficient buildings, **Fig. 6** right.

Table 6

Annual energy use in studied day-care centres

	Energy use, kWh/(m^2 a)				
	Estonia 1	Estonia 2	Finland 1	Finland 2	Norway
Delivered energy					
Designed	146	45	133	71	71
Measured	202	125	327	121	46
Performance gap	28%	64%	59%	41%	-54%
Energy Performance Value (Primary energy)					
Designed	189	83	169	152	-
Measured	251	249	401	258	-
Performance gap	25%	67%	58%	41%	-

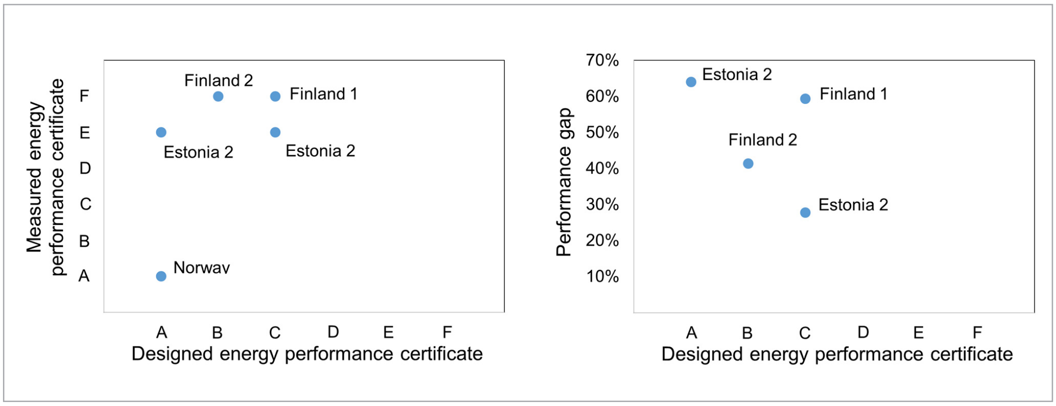

Fig. 6

Comparison between designed and real measured energy performance certificate (left) and dependence of performance gap on designed energy performance certificate in buildings where energy performance targets were not fulfilled

Discussion

Measured real energy use was higher, or even significantly higher, than the energy use calculated during the design phase. Raide et al. (2015) monitored and simulated performance of energy use, indoor climate, and building service systems of the day-care center that was designed according to passive house standards. Buildings did not meet the desired levels because of a lack of robust project leadership and final component selection. Because of a too simplified control of building service systems and over optimistic and inadequate assumptions in energy calculations and initial data, energy performance targets were not realised. The energy performance gap was larger for more energy efficient buildings. When energy use is small, then small changes may cause a large relative difference. Arumägi and Kalamees (2016) showed that in designing of very energy efficient buildings, more thorough analyses are needed in the very first stage of the design, to find suitable solutions and possible compromises. If, in today's design practice, during the preliminary design phase, only minor analysis is done, then design practice should change when moving towards nZEB.

Norwegian day-care center that was designed, constructed and commissioned according to passive house standards fulfilled EPC promises. Even more – measured real energy use was smaller than designed. A more accurate and robust commissioning, design and construction process is needed for future nZEB day-care centers.

The exact reason of higher energy use was difficult to determine. The total energy use was measured, but there lack detailed and separated energy measuring of energy use in smaller subdivision. For future nZEB day care centers we recommend measuring separately:

- heat consumption for room heating, heating of ventilation air, heating of DHW,
- electricity consumption for fans-pumps, appliance-lightning, cooling
- on-site energy production: heat, electricity.

Potential reasons for the higher measured energy use are caused by the methodology of the energy calculations and the differences in user behavior. Some of the appliances, which may have a significant share of the buildings overall energy consumption, like hot kitchens, missing of heat recovery unit in kitchens, swimming pools, and outdoor lighting, are not taken into account in the energy calculations. Indoor temperature during the heating season tended to be higher than the +21 ºC used in the energy calculations. Measurements showed that occupants preferred an indoor temperature around +22…+23 ºC. Also usage activity and occupant density influence energy use. Sekki et al. (2015) studied day-care centers in Finland and showed that the more m^2/child, the more energy the building consumes (even then, there were great variations between the buildings (Sekki et al., 2015b)). Therefore, we recommend making energy simulations based as much as possible on the future building's usage profile, as well as standard simulations.

The designed delivered energy use in Finnish day care center 2 was 71 kWh/(m^2·K). Sankelo et al. (2018) showed that with the similar initial investment cost it would be possible to reach to much lower energy use and cost optimal levels for day-care centres lie on 35 – 40 kWh/(m^2·K) for buildings with GSHP and 70 – 80 kWh/(m^2·K) for buildings with district heating.

Thermal environment corresponded to the climate categories I and II better during heating season. During summer season the room temperature was too cool mainly because of low spring-summer period.

Even though measured ventilation air flow rates did not fulfill designed values, based on CO_2 levels, indoor air quality targets were fulfilled most of the time. This indicates that window airing was used to compensate for missing ventilation airflow. Window airing does not provide any heat recovery or filtration possibilities. This could cause a deterioration of indoor air quality (depending on the location of the building) and energy performance.

Conclusions

Indoor climate condition measurements showed that, in general, the thermal environment and indoor air quality in 5 modern day-care centres in Estonia, Finland and Norways corresponded to the highest indoor climate categories I and II (EN 15251). Building heating and ventilation systems in the studied buildings are working without major problems. Good indoor climate conditions were also reflected in the occupant satisfaction questionnaires. For most of the studied buildings, over 80% of the people marked all indoor environment condition parameters (thermal comfort, indoor air quality, acoustics, odour and illuminance) as acceptable.

Energy consumption analysis showed that problems exist between the calculated and measured values. In most of the studied buildings, measured energy consumption is higher or even significantly higher than designed values. Potential causes of the higher actual energy consumption are caused by differences between measured and designed solutions, the methodology of the energy calculations and the differences in user behaviour. Some of the appliances, which may have a significant share of the buildings overall energy consumption, like hot kitchens, swimming pools and outdoor lighting are not taken into account in the energy calculations. Indoor temperature in the heating season tended to be higher than the 21 ºC used in the energy calculations. Measurements showed that occupants prefer an indoor temperature of around 22…23 ºC.

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About the Authors

KALLE KUUSK

Senior Research Scientist

Tallinn University of Technology, Estonia

Main research area

Energy performance of buildings

Address

Ehitajate tee 5, Tallinn
E-mail:
kalle.kuusk@taltech.ee

JAN JOHANSSON

Energy Manager

Växjö Kommun, Sweden

Main research area

Energy performance of buildings

Address

Västra Esplanaden 18, Växjö
E-mail: jan.johansson3@vaxjo.se

ENDRIK ARUMÄGI

Senior Research Scientist

Tallinn University of Technology, Estonia

Main research area

Energy performance of buildings

Address

Ehitajate tee 5, Tallinn
E-mail: endrik.arumagi@taltech.ee

JAREK KURNITSKI

Adjunct Professor

Aalto University, Finland

Main research area

Energy performance of buildings

Address

Otakaari 1 B, Espoo
E-mail:
jarek.kurnitski@aalto.fi

AHMED KAISER

Doctoral Candidate

Aalto University, Finland

Main research area

Energy performance of buildings

Address

Otakaari 1 B, Espoo
E-mail:
kaiser.ahmed@aalto.fi

TERO HASU

Specialist

Kouvola Innovation Ltd., Finland

Main research area

Energy performance of buildings

Address

Paraatikenttä 4, Kouvola
E-mail: tero.hasu@kinno.fi

KRISTO KALBE

Expert

Tallinn University of Technology, Estonia

Main research area

Energy performance of buildings

Address

Ehitajate tee 5, Tallinn
E-mail: kristo.kalbe@taltech.ee

TARGO KALAMEES

Professor

Tallinn University of Technology, Estonia

Main research area

Energy performance of buildings

Address

Ehitajate tee 5, Tallinn
E-mail: targo.kalamees@taltech.ee

NICOLA LOLLI

Research Scientist

SINTEF, Norway

Main research area

Energy performance of buildings

Address

Strindveien 4, Trondheim
E-mail: nicola.lolli@sintef.no

ANNE GUNNARSHAUG LIEN

Senior Research Scientist

SINTEF, Norway

Main research area

Energy performance of buildings

Address

Strindveien 4, Trondheim
E-mail: anne.g.lien@sintef.no

JAANUS HALLIK

Doctoral Candidate

Tallinn University of Technology, Estonia

Main research area

Energy performance of buildings

Address

Ehitajate tee 5, Tallinn
E-mail: jaanus.hallik@taltech.ee