Understanding the performance gap of nearly zero-energy schools in Belgium

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Abstract: This study aims to understand the energy use performance gap of Passive House (PH) schools and nearly zero-energy schools (nZES). The study reports the results of a recent field survey conducted on thirty nearly zero energy buildings constructed between 2015 and 2020. An analysis of energy consumption (electricity and natural gas) and a walkthrough survey were conducted. A representative simulation building energy data set and a reference model was created. The average energy use intensity per school (primary and secondary) was 59 and 42 kWh/m^2/year. The paper provides insights into the underlying causes of a discrepancy between predicted and measured energy use. Findings on energy needs and use intensity are useful in temperate and continental climates.

Keywords: performance gap; energy model; energy audit; calibration

1. Introduction

The European Energy Performance of Buildings Directive (EPBD) requires all new buildings to be nearly zero-energy buildings (nZEB) by 31 December 2020. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby. Combining renewable energy and resource efficiency can play an essential role in the transition towards sustainability and carbon neutrality.

One of the fastest-growing sectors in Europe is educational buildings. According to Eurostat data (2018), the annual student population is growing. Before 2050, all member states will need to ensure a minimum growth of more than 40,000 new classrooms. Several national and regional governments have a target date of 2021 for every new school to be actively working on becoming energy neutral. In Belgium, education buildings are responsible for 1.5% of Belgium' greenhouse gas emissions (SPF, 2019).

The Passive House concept was strongly adopted in Belgium and evolved to be nearly Zero Energy Building concept. Between 2013 and 2019, more than 50 new nearly Zero Energy Schools (nZES) were constructed, but these new schools are challenging to evaluate. nZES are high-tech buildings that try to balance high indoor air quality and comfort conditions while keeping the ultra-low energy use target (De Reys, 2019). The determination of the boundary conditions, design strategies, and solutions for those schools remains challenging (Wauman *et al.*, 2010).

A substantial knowledge gap in reliable benchmark models for high-performance schools makes it difficult for policy-makers and building professionals worldwide to evaluate the success of their policies and designs (Hernandez *et al.*, 2008). This study' first objective is to conduct a field survey that reports building characteristics and end-use of energy patterns and energy costs. The second objective is to create a valid and up-to-date benchmark model of nearly zero-energy schools in Belgium.

This paper is based on Attia (2020) work and presents two simulation reference models created based on monitoring and analyzing 30 high-performance schools in Belgium. The approach aims to develop two benchmark buildings that are representative of the new schools built-in 2015-2018. The reference models are documented and implemented to use with the EnergyPlus energy simulation program. At the same time, the study provides insights on the energy performance discrepancies of nZES in cold, mild temperate and continental climates. Cities falling in those two regions will improve their understanding of the energy consumption of high-performance schools and how they can better monitor and control it.

2. Methodology

2.1. Literature review

A literature review was conducted, including recent international publications that aimed to develop energy performance benchmarks for school buildings. Then, the research scope and focus were narrowed to Passive House schools and nZES. A local literature review followed this in the Belgian context.

2.2. Creation of a database for nearly zero energy schools in Belgium

The current study follows a cross-sectional study design where information was collected from literature and using a survey. An initial database was created and included schools built after 2013 that comply or exceed the requirements of the Belgian Passive House Standard (PHS). The PHS requires a highly insulated and airtight envelope (an air permeability of less than of 0,6vol/h at 50 Pa) (Moniteur Belge, 2008) with a net heating energy demand and net cooling energy demand ≤ of 15 kWh/m².year (AGION, 2015). The energy demand for heating and cooling should be calculated using a quasi-steady-state calculation method; the Passive House Planning Package (PHPP) 2007 (Passive House Institute, 2007). The school should include mechanical ventilation with heat recovery (MVHR) (Feist *et al.*, 2005), and a zone is considered overheated when 5 percent of its occupied period exceeds 25°C (Mlecnik *et al.*, 2011).

The database included several details on each school: location, construction age, occupancy density, measured energy heating and cooling, energy use intensity, energy performance certificate details, measured envelope airtightness, compactness of geometry, and construction cost. A final list and complete list of thirty schools were created to focus on energy efficiency and costs for nZESs for 2015-2018. The sample size was narrowed down in relation to data accuracy and completion—the analysis of the collected data involved finding a correlation between the construction costs and the energy performance.

2.3. Selection of the representative reference schools

According to literature, there are three main approaches to create reference models (Corgnati *et al.*, 2013). The most common method is to develop theoretical reference models based on statistical data of the energy performance or thermal comfort of similar building typologies and functions in similar climates. In this approach, a typical meteorological weather file can be used. Because the data collected for the thirty nZESs were abundant, this modeling approach was chosen for the study.

A typology analysis took place for the thirty schools to select two representative building configurations. Plans and forms of thirty school configurations were described and analyzed, and Brussels typical meteorological year was chosen to perform the simulations. Overall, Belgium's climate is mild-cold and humid, with a significant amount of rainfall during the year.

2.4. Energy characteristics of representative schools

Two types of energy audits were conducted for the selected school buildings (Krarti, 2016). An analysis of energy consumption (electricity and natural gas) for the occupancy period of 2015-2018 was based on monthly consumption data. This step allowed understanding the building performance and identifying the pattern of use, peak demand, and seasonal climate impact. The second type of audit was based on walkthrough visits to identify and characterize the energy systems. This was followed by the envelope's characterization, aiming to identify the construction composition, air tightness, window types, and solar protection.

A survey was used to identify the occupancy density and profiles in classrooms based on a seasonal, monthly, weekly, and daily level. The survey addresses both school teachers and students, and once a repetition of the answers pattern was found, the survey was stopped. The collected data were compiled and analyzed to reflect the energy performance of realistic classroom operation situations when mechanical ventilation, space heating, and space cooling are turned on.

2.4.1. Occupancy density and profiles

Data were uploaded into a geodatabase that is used to store geo-referenced information. Data from all surveyed were analyzed holistically to ensure data integration across all sectors. The annual occupancy schedule has been set based on the Flemish and Walloon 2018-2019 annual teaching schedule because most of the case studies were in this region. The holidays have been subtracted from the occupancy schedule.

2.4.2. HVAC systems and comfort set points

A special section in the energy audit involved characterizing the HVAC systems and energy sources. The Domestic Hot Water use (DHW) and consumption were identified from water meters, and the delivered water temperatures were measured. The airflow rate of the MVHR system was measured during different moments of the day to estimate the mechanical ventilation schedule. Also, the Building Management Systems (BMS) was checked, and the required data points for comfort control and management built and connected to field devices were reviewed. The programming and setpoint conditions for air conditioning and boilers were identified.

2.4.3. Lighting load intensity

The lighting of common areas and classrooms was reviewed, and occupancy control was identified. The luminaire type has been described, and it has been supposed that all the lighting equipment in the school were recessed.

2.4.4. Plug load intensity and schedules

An inventory of electrical appliances took place to determine the plug load intensities, as-well-as their operation schedules. The average class electrical appliances' presence and running hours were selected based on the field survey and walkthrough audit, and the plug load intensity was calculated based on appliance catalogs. To facilitate and unify the data on plug loads, all appliance powers were summarized less than one unit of power density for the estimated model.

2.5. Development of the benchmark models

Two representative simulation models were made based on the previously described selection process and building characterization. The validity of the estimate has been further checked against the public statistics and verified through a model calibration and utility bill comparison.

The simulations have been performed through the dynamic energy modeling software tool EnergyPlus (Version 8.2.0) (DOE, 2019). Calibration was done for evaluating the goodness-of-fit of the school buildings energy models according to ASHRAE Guideline 14 (Guideline, 2002) and using the whole building calibrated simulation approach (calibrated simulation). The guideline uses two indices to evaluate the goodness-of-fit of the building energy model. The Mean bias error, MBE, and the Coefficient of variation of the Root mean square error, CV(RMSE). MBE is a non-dimensional measure of the overall bias error between the measured and simulated data in a known time resolution, and it is usually expressed as a percentage:

$$\mathrm{MBE} = \frac{\sum_{i=1}^{N_p}(m_i - S_i)}{\sum_{i=1}^{N_p} m_i}\ [\%] \tag{1}$$

Where:

m_i = measured data; S_i = simulated data at time interval i; N_p = total number of data values.

CV (RMSE) represents how well the simulation model describes the variability in the measured data. It is defined as:

$$\mathrm{CV(RMSE)} = \frac{1}{m}\sqrt{\frac{\sum_{i=1}^{N_p}(m_i - S_i)^2}{N_p}}\ [\%] \tag{2}$$

Where:

m_i = measured data; S_i = simulated data at time interval i; N_p = total number of data values; m = average of measured data values.

According to the ASHRAE Guideline 14, the simulation model is considered calibrated if it has MBE that is not larger than 5% and CV(RMSE) that is not larger than 15% when the monthly data are used for the calibration. To get a reliable building energy model and increase the accuracy of estimating the building's performance, the models of schools underwent two subsequent calibrations. The building model was first calibrated on the basis of the building's measured monthly gas consumption ad was then refined in free-running with a second calibration concerning monitored hourly indoor air temperatures (Pagliano *et al.*, 2016).

Hopfe *et al.* (2011) identified the independent variables that influence the performances of the building and are mostly affected by uncertainty. In this study, the class sizes are fixed and are not considered as a design variable. As the surveys and energy audits allowed to precisely quantify the type of windows, the power density of the electric equipment, and lighting, these parameters are not sources of significant uncertainty (Causone *et* *al*., 2015). The calibration process focused on independent testing variables that describe airtightness and the occupant density and schedule, and the heating system's global seasonal efficiency.

3. Results

3.1. Database for nearly zero energy schools

The database lists thirty projects that complied with the Belgian Passive House Standard requirements. The database includes the most critical energy performance indicators: occupant density, heating and cooling energy use, energy use intensity, and cost. The energy performance data represents the yearly average values collection between 2015 and 2018. The complete database can be found in the work of Attia *et al.* (2020).

3.1.1. Energy use intensity

The survey revealed that the average total energy use intensity was 50 kWh/m^2/year in 2015-2018. As shown in Figure 1, the schools are heating-dominated, and we could conclude that several schools had overheating problems. The major energy use is electric represented by the blue and yellow color: electricity forms almost two-thirds of total energy use. This is mainly due to the mechanical ventilation and plug loads.

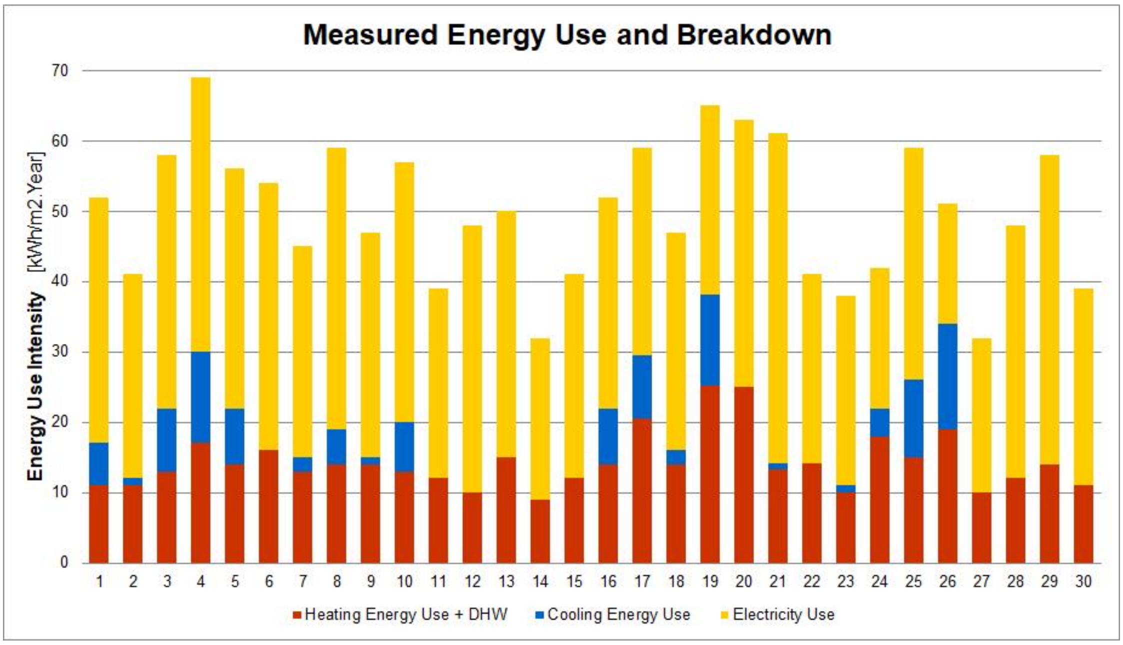

Figure 1: Measured energy use and breakdown

3.1.2. cost

The average cost for the thirty investigated project was 1450 euros per square meter. There was no correlation between the energy use intensity and the cost to be found. This cost is lower than the average schools' price in the same period, which is around 1500 euros/m^2 (Dhondt, 2018).

3.2. Selected reference schools

Plans and forms of thirty school configurations were analyzed, and the rectangular classroom shape was found across all investigated plans. Two groups of schools were identified from the data collected: primary schools having two floors and a compact mass and secondary school with less compact plans and an average of 4 floors. Both typologies had to be distinguished due to the disparity regarding use, floor layout, building configuration, occupancy density, and energy performance. As shown in Figure 2 and Figure 3, two typical school typologies were identified and referred to as Typology 1 and 2. For this study, both typologies were selected and identified as representative nZES buildings.

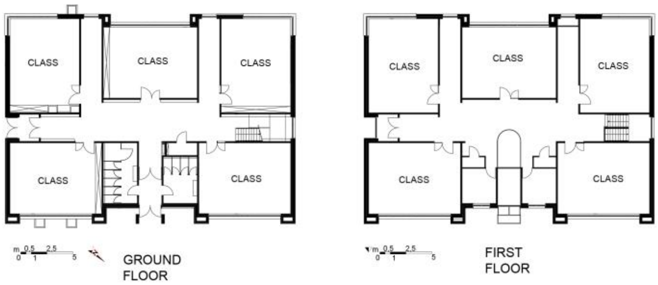

Figure 2: Floor plans of the primary school

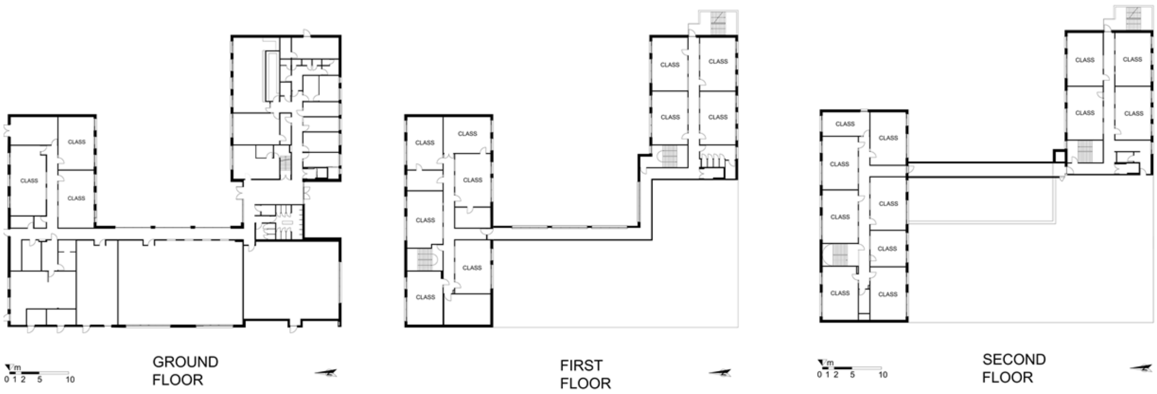

Figure 3: Floor plans of the secondary school

3.2.1. School buildings description

Both selected typologies were positioned on flat terrain, without surrounding trees or other obstructions that can cast shade on the building mass. The basic building construction is reinforced-concrete post and column with 0.65 m concrete hollow blocks walls with 30cm rigid polystyrene panels insulation. Windows are triple-glazed, coated, and transparent with a conductivity of 0.8 W/m^{2}K and SHGC as low as 0.5. The total amount of glass in North and South facades is estimated to be between 25% and 45% of the total wall area. There is no solar protection for the facades, and most windows have an internal blind. The average occupancy density for both selected typologies was calculated based on the average area and number of students per classroom for all investigated schools. Table 1 presents the values of average classroom density values for nZES primary and secondary schools in Belgium.

Table 1: Classroom average occupancy density in primary and secondary schools

	Primary school	Secondary school
Occupancy density (Bruto) [m^2/student]	7.2	12
Occupancy density (Netto) [m^2/student]	2.5	2.8

As recommended by ASHRAE Standard 90.1 Appendix G (ASHRAE, 2004), the benchmark model performance was generated by simulating the building with its actual orientation and again after rotating the entire building 90, 180, 270 degrees, then averaging the results.

3.3. Energy characterization of reference schools

3.3.1. Energy use intensity

The average energy use intensity for the reference primary school is 59 kWh/m^2/year. For the reference secondary school, the average energy use intensity is 42 kWh/m^2/year.

3.3.2. Occupancy density and schedules

Based on available data, the occupancy period was defined from 7:00 to 18:00 on weekdays, while on the weekend, the building is considered empty. The model takes into account pupils' occupancy schedules, as-well-as school employees' presence. Absenteeism of 5% is taken into account with an operational schedule of 190 academic days. As shown in Figure 4, a lunch break is assumed daily between 12:00 and 13:00, where students leave the school or go to a commonplace.

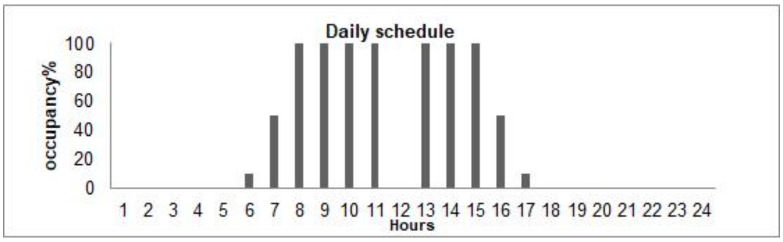

Figure 4: Occupation schedule for the two school buildings

3.3.3. Internal load intensities (plug load intensity and schedules)

The clothing insulation and metabolic heat production were estimated based on NBN-EN 15251 (CEN, 2007) and ter Mors (2011). The occupant internal heat gains were estimated to be 80 W/pers, and the equipment heat gains were estimated to be 1 W/m^2. All classrooms were modeled without computers: only teachers might have access to PCs in the school, and therefore, it was considered as negligible.

3.3.4. HVAC systems and comfort set points

In both reference schools, mechanical ventilation with heat recovery is installed. The HVAC system is coupled to an air handling unit with a Constant Air Volume (CAV) system to provide the minimum amount of fresh air per person of 20 m^3/h based on the average Flemish and Walloon EPBD requirements (NBN EN 13799) (CEN, 2007). The reference case has been modeled using an HVAC template with a CAV. A user profile schedule controls the air handling units. An air-to-air heat exchanger is bypassed when the indoor operative temperature is lower than the indoor air temperature. Each classroom is pre-ventilated for 1 hour before the start of the school. The minimum supply air temperature is 16°C. The heat recovery system preheats the air with an efficiency of 75%.

The gas-fired boiler was modeled with an average a Coefficient of Performance (COP) of 0.9 coupled to the hot water loop for heating and sanitary hot water. The rooms' set point temperature is 20°C (minimum 16°C). Both selected schools had a mechanical cooling system and were modeled with a mechanical cooling system (Variable Refrigerant Flow (VRF) system).

3.3.5. Lighting lead intensity

Lighting systems had a power consumption of 6 W/m^2 and was programmed in EnergyPlus as 2W/m^2 per 100 Lux of light level. Then, a 300 lux threshold was used to reach the 6 W/m^2. A daylight control system is coupled to a centrally positioned daylight sensor. The required illuminance of each classroom is specified in NBN EN 12464-1 (CEN, 2002).

3.3.6. Simulation model and validation

Two representative simulation models were built considering the previously described envelope, occupancy and energy systems, and characteristics. The principal model input parameter values are listed by Attia *et al.* (2020).

3.3.7. Numerical model calibration

The MBE and CV(RMSE) of monthly energy use for four consecutive years are calculated for both school models and reported in Table 2. Figure 5 and Figure 6 show the estimated gas use simulated in both models and the real gas use of both actual buildings. A good agreement was found in the monthly energy use behavior and curve shapes between the simulated data and the collected data. Figure 7 and Figure 8 show the estimated electricity use simulated in both models and the real electricity use of both actual buildings. Lower extremes represent the lowest and highest measured monthly electricity use. The upper and lower quartile of the red box includes 80% of the monthly measurements.

Table 2: MBE and CV(RMSE) if the monthly energy use of both reference school models from 2015 to 2018

	2016		2017		2018		2019	
Statistical indices	MBE (%)	CV(RMSE) (%)	MBE (%)	CV(RMSE) (%)	MBE (%)	CV(RMSE) (%)	MBE (%)	CV(RMSE) (%)
Reference school 1 monthly calibration (natural gas)	+5	-14	-6	-12	-2	-8	-3	-11
Reference school 1 monthly calibration (electricity)	5	10	3	14	4	12	4	12
Reference school 2 monthly calibration (natural gas)	3	14	4	10	4	9	4	11
Reference school 2 monthly calibration (electricity)	4	17	5	11	5	11	5	14

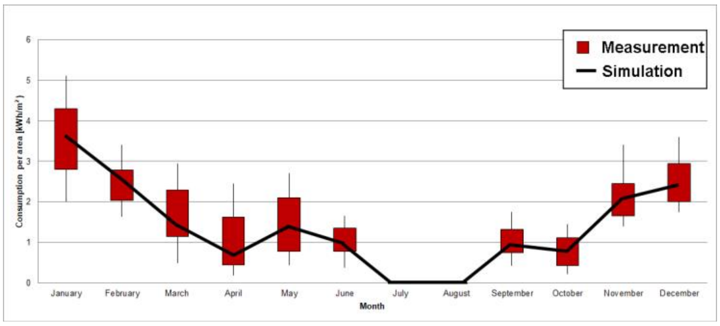

Figure 5: Surveyed and simulated monthly gas use of the primary school

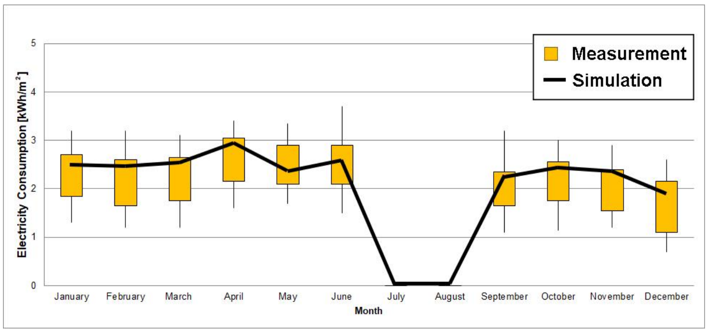

Figure 6: Surveyed and simulated monthly gas use of the secondary school

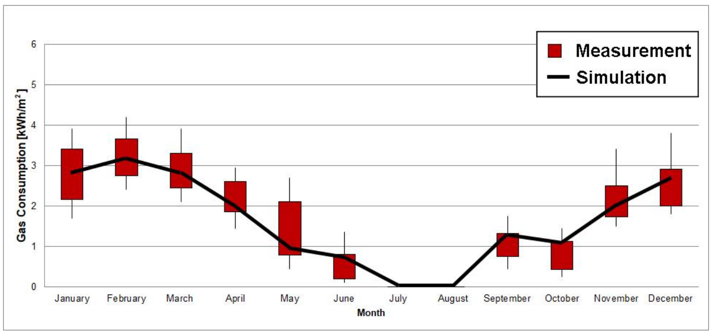

Figure 7: Surveyed and simulated monthly electricity use of the primary school

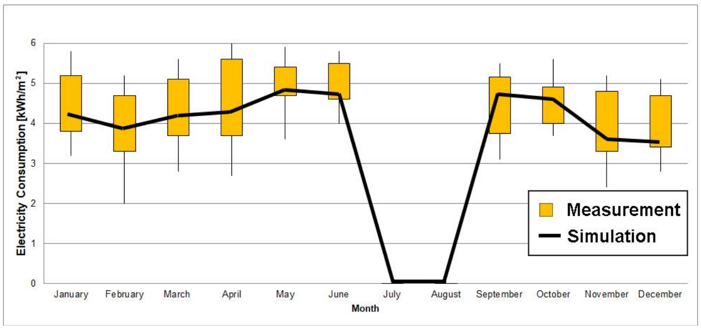

Figure 8: Surveyed and simulated monthly electricity use of the secondary school

4. Discussion

Two reference models for nearly Zero Energy Schools (nZES), represented primary and secondary schools recently built in Belgium, were developed and validated in this study. Benchmarking those newly constructed schools serves as a mechanism to evaluate and assess their real energy performance of buildings over time and share learned lessons. Benchmarking allows characterizing them through reference models to enable reliable simulations and future improvement.

4.1. Strength and limitations of the study

European experts in several organizations, including the Buildings Performance Institute Europe (BPIE), explicitly identified the need to create benchmark models validated and that can be used to assess energy use, indoor environmental quality, and user interaction in high-performance buildings (Atanasiu and Attia, 2011).

Benchmark models significantly influence the design decision-making during design and building energy use and indoor environmental quality during operation (Toleikyte *et al.*, 2016). The implications of energy efficiency on building thermal comfort are severe, and climate change can jeopardize many efforts to reduce the cooling requirements and cooling systems (Yang and Lam, 2014). Benchmark models provide more significant resources for energy modelers and energy simulation experts and allow them to bridge the energy performance gap between operational and designed performance (Dasgupta *et al*., 2012). They can also be useful for sale or rental purposes.

Another benefit of our two benchmark models is to inform regulation and the regional EPBD experts. The study succeeded in characterizing both reference schools in a prescriptive and performance-based way, which can be vital in changing the regulatory compliance and certification process (Hernandez *et al*., 2008). The study can also be useful in countries with temperate and continental climates.

The model was calibrated using monthly data for almost four years. Ideally, it should have been tested against hourly operative temperature data, and the variations in occupancy should have been more investigated. The limits of the thirty cases database were pushed to get a good representative sample of the nZES building stock performance that can be developed in the future. However, the used cases were all built-in 2013-2018 with very similar energy performance requirements.

Another limitation is that indoor temperature and air change rates have been assigned standard and estimated values. The benchmark models succeeded in characterizing geometry, envelope, occupancy, and HVAC systems directly related to thermal and energy performance. There is a necessity to define the ventilation rates required in those school spaces about the energy losses and the mechanical ventilation systems' overall efficiency, including heat recovery. The findings indicate that most schools' energy use is electric as an effect of IAQ ventilation.

4.2. Implications for practice and future research

Future work should address indoor environmental quality and portray IAQ ventilation's adverse effect on energy use intensity. Future research should also test our building models with the occupant in the broader context and with a large sample of students concerning indoor environmental quality (Attia *et al.*, 2019). More work is also needed to compare our benchmark model results to estimate the nZEB-tool developed by the PHPP (Kern, 2019). The use of multi-zone dynamic simulation models would lead to less discrepancy between the assumed modeling input and real occupancy and operation conditions concerning ventilation systems and air change rates (Allaerts *et al.*, 2017).

The implication of our work on practice can lead to revision of the EPBD and Belgian Passive House Standard requirements (PMP and Pixii). A comparison can be made during early design stages to assess and evaluate different design assumptions and boundary conditions. Countries with temperate climate in Europe and worldwide could adopt our benchmark models and refine them accordingly to estimate and assess the energy performance of nZES in their context.

This research provided a detailed characterization of the energy performance gap in recently construction high-performance schools. Future research should extend the focus on breaking down the electricity use under more items and measure their validity and relevance. Heat gains, lack of solar protection, and air change rates are the most critical parameters that influence the energy performance of nZES (Attia and Gobin, 2020). Future detailed audits should take place to assess the operation and model assumptions of mechanical ventilation systems. Further research and adoption of the same benchmark models would be excellent avenues for further research for further validating and generalizing the proposed models for nZES design and operation.

5. Conclusion

In this study, the energy use intensity and energy use breakdown of thirty nearly Zero Energy Schools (nZES), located in various areas throughout Belgium, is estimated and compared based on four-year measurement data (2015-2018). Two representative reference models were created and calibrated using EnergyPlus software. Study results indicate that both created reference models have a good validity in assessing the energy performance of nearly Zero Energy Schools built between 2015 and 2018 in Belgium. The models are reliable and consistent and can be used by future building energy modelers and experts. The models were calibrated according to ASHRAE Guideline 14 using two indices to evaluate the goodness-of-fit of the building energy model. The Mean bias error, MBE, and the Coefficient of variation of the Root mean square error, CV(RMSE), were used to prove that both model are accurate and valid.

The dominant energy use of electricity in Belgian nZES is mainly related to the intensive use of mechanical ventilation and electric installations. Most of the investigated schools succeeded in decreasing the energy needs for heating and cooling. However, thermal comfort, which was not investigated in this study, seems to be problematic. The cooing use was significant in a temperature climate such as Belgium and in schools, which are only occupied 27% (in average 2360 hours/yearly) of the year. The lack of solar protection for largely glazed facades, the lack of thermal inertia activation due tonight cooling blocking (for security reasons) are among the reasons for cooling energy needs increase.

The study highlights that most of those schools were built at a similar cost per square meter. The small variance is mainly due to the strict budget control maintained during the project delivery process. In this context, the study provided valuable insights on the cost.

Finally, the study provides several insights on the reference schools building and systems characteristics. The result confirms a significant energy performance gap between the early design performance assumptions and the real performance. The models can guide school design decisions, operators, and school owners about the energy performance and energy use intensity and characterize nearly Zero Energy Schools.

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References

S. Attia, N. Shadmanfar, F. Ricci, "Developing two benchmark models for nearly zero energy schools," Applied Energy, 2020, vol. 263, p. 114614.

E. Recast, "Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)," *Off. J. Eur. Union*, vol. 18, no. 06, p. 2010, 2010.

SPF, "The contribution of the main sectors to total emissions and their evolution share of different sectors in Belgium," 2017. [Online]. Available: https://www.climat.be/fr-be/changements-climatiques/en-belgique/emissions-belges/emissions-par-secteur/. [Accessed: 11-May-2019].

G. De Reys, "Remediëring oververhittingsrisico passiefschool op basis van dynamische simulaties."

B. Wauman, R. Klein, H. Breesch, S. Van Loon, R. Baetens, and D. Saelens, "Determination of boundary conditions for passive schools: impact on net energy demand for heating and cooling," in *Workshop/studio*, 2010, vol. 44, p. 100.

P. Hernandez, K. Burke, and J. O. Lewis, "Development of energy performance benchmarks and building energy ratings for non-domestic buildings: An example for Irish primary schools," *Energy Build.*, vol. 40, no. 3, pp. 249–254, 2008.

Deprez, Bernard, "Be.passive: Schools," no. 3, p. 92, 2010.

AkkP 33, *Passivhaus-Schulen, Protokollband Nr. 33 des Arbeitskreises kostengünstige Passivhäuser Phase III*. Darmstadt: Passive House Institute, 2006.

Moniteur Belge, "Flemish Government Decree concerning energy performances in school buildings, in Flemish: Belgisch Staatsblad, Besluit van de Vlaamse Regering tot regeling van een aantal aangelegenheden ter uitvoering van het decreet van 7 december 2007 betreffende energieprestaties in scholen," no. 2007, p. 235, 2008.

AGION, "Pilootproject Passiefscholen Bilan 2015," AGION, Brussels, 2015.

Passive House Institute, *Passivhaus Projektierungspaket (PHPP) version 2007*. 2007.

W. Feist, J. Schnieders, V. Dorer, and A. Haas, "Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept," *Energy Build.*, vol. 37, no. 11, pp. 1186–1203, 2005.

E. Mlecnik, S. G. M. Attia, and S. Van Loon, "Net zero energy building: A review of current definitions and definition development in Belgium," in *Passive house Symposium*, 2011, vol. 1.

S. P. Corgnati, E. Fabrizio, M. Filippi, and V. Monetti, "Reference buildings for cost optimal analysis: Method of definition and application," *Appl. Energy*, vol. 102, pp. 983–993, 2013.

M. Krarti, *Energy audit of building systems: an engineering approach*. CRC press, 2016.

DOE, "EnergyPlus." [Online]. Available: https://energyplus.net/. [Accessed: 12-Dec-2019].

A. Guideline, "Guideline 14-2002, Measurement of Energy and Demand Savings," *Am. Soc. Heat. Vent. Air Cond. Eng. Atlanta Ga.*, 2002.

L. Pagliano, S. Carlucci, F. Causone, A. Moazami, and G. Cattarin, "Energy retrofit for a climate resilient child care centre," *Energy Build.*, vol. 127, pp. 1117–1132, 2016.

C. J. Hopfe and J. L. Hensen, "Uncertainty analysis in building performance simulation for design support," *Energy Build.*, vol. 43, no. 10, pp. 2798–2805, 2011.

F. Causone, S. Carlucci, A. Moazami, G. Cattarin, and L. Pagliano, "Retrofit of a kindergarten targeting zero energy balance," *Energy Procedia*, vol. 78, pp. 991–996, 2015.

K. Dhondt, "Average Construction Cost' Schools of Tomorrow,'" 14-Jun-2018.

A. S. ASHRAE, "Standard 90.1-2004, Energy standard for buildings except low rise residential buildings," *Am. Soc. Heat. Refrig. Air-Cond. Eng. Inc*, 2004.

E. CEN, "15251: 2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics," *Bruss. Belg.*, 2007.

S. ter Mors, J. L. Hensen, M. G. Loomans, and A. C. Boerstra, "Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts," *Build. Environ.*, vol. 46, no. 12, pp. 2454–2461, 2011.

CEN, "Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems," CEN, Brussels, 2007.

C. E. de Normalisation, "EN 12464-1: Light and Lighting-Lighting of work places, Part 1: Indoor work places," *Com. Eur. Norm.*, 2002.

A. Toleikyte *et al.*, "ZEBRA 2020-Nearly zero-energy building strategy 2020. Strategies for a nearly Zero-Energy Building market transition in the European Union," 2016.

L. Yang, H. Yan, and J. C. Lam, "Thermal comfort and building energy consumption implications–a review," *Appl. Energy*, vol. 115, pp. 164–173, 2014.

A. Dasgupta, A. Prodromou, and D. Mumovic, "Operational versus designed performance of low carbon schools in England: Bridging a credibility gap," *HVACR Res.*, vol. 18, no. 1–2, pp. 37–50, 2012.

S. Attia, S. Garat, and M. Cools, "Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades," *Build. Environ.*, vol. 157, pp. 268–276, 2019.

Kern, Handboek nZEB-tool, voor het ontwerpen van een (nearly) Zero Energy Building. Ede, The Netherlands: Kennis Instituut Kern, 2019.

K. Allaerts, J. Al Koussa, J. Desmedt, and R. Salenbien, "Improving the energy efficiency of ground-source heat pump systems in heating dominated school buildings: A case study in Belgium," Energy Build., vol. 138, pp. 559–568, 2017.

S. Attia, C. Gobin, "Climate Change Effects on Belgian Households: A Case Study of a Nearly Zero Energy Building". Energies, 13(20), 5357, 2020.