Assessment of HVAC generation and emission performance methods in the context of zero-emission buildings in Italy

Franz Bianco Mauthe Degerfeld[1*], *Ilaria* Ballarini[1], and *Vincenzo* Corrado[1]

[1]Politecnico di Torino, Department of Energy “Galileo Ferraris”, 10129 Turin, Italy

Abstract. The revised Energy Performance of Buildings Directive (EPBD) establishes a clear trajectory toward a decarbonised building stock, in which the refurbishment and delivery of zero-emission buildings play a central role. A key challenge in this transition lies in selecting the appropriate methods for assessing the building energy performance, balancing the need for accuracy with the practicality of simplified approaches. This work analyses a representative Italian building, first in its current state and then as refurbished to comply with the zero-emission building requirements defined in the Italian context. Starting from the mandatory national monthly calculation procedures, the analysis is extended to enhanced hourly simplified methods and detailed simulations for assessing the performance of technical building systems. The results highlight methodological differences among these approaches and quantify the impact of varying assumptions on system efficiency and on primary energy use. Particular attention is given to verifying whether a building deemed compliant under the national monthly method, still meets zero-emission energy-efficiency targets when assessed through more detailed procedures. Results provide insight into the robustness of current compliance procedures and support a more consistent implementation of EPBD requirements within the national practice.

1 Introduction

The decarbonisation of the building sector is one of the focal points in the European Union’s climate neutrality pathways. Due to the significant impact of buildings on greenhouse gases (GHG) emissions and to the long life cycle of buildings, actions are critical. The latest recast of the Energy Performance of Buildings Directive recast (EPBD) [1] indicated the transformation of both new constructions and existing ones into zero-emission buildings (ZeB).

A ZeB is defined as a building with very high energy performance, requiring zero or very low energy, producing zero on-site carbon emissions from fossil fuels, and achieving zero or very low operational GHG emissions. In operational terms, the annual primary energy use of a ZeB may be met through renewable energy sources generated on-site or nearby, renewable

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[*] Corresponding author: franz.bianco@polito.it

energy supplied through energy communities, efficient district heating and cooling, and other carbon-free sources. The ZeB target thus extends beyond the traditional high-efficiency building concept by combining (i) energy demand reduction, (ii) high system efficiency, (iii) renewable and carbon-free energy sources, and (iv) reduction of the impact of the whole life of buildings.

A key implication of the EPBD is the growing need to assess building performance holistically and with transparent metrics. In addition to energy indicators (e.g., primary energy, renewable energy ratio), the recast Directive strengthens the role of GHG accounting, distinguishing operational emissions from whole-life impacts. Operational emissions are driven mainly by delivered energy and emission factors, while whole-life indicators (e.g., life-cycle global warming potential) expand the boundary to include embodied impacts of materials and systems, with future threshold values expected for new buildings.

In Italy, the implementation of the ZeB concept will necessarily interact with the established NZEB framework and with national calculation rules (e.g., primary energy factors and operational emission coefficients used in regulatory compliance). Furthermore, the results can be highly sensitive to the adopted conversion factors and to the assumed degree of decarbonisation of the electricity mix and district energy networks. This creates a methodological challenge: the same HVAC solution (e.g., heat pumps, district heating, hybrid systems) may lead to different conclusions depending on whether the assessment emphasises final energy, primary energy, or operational GHG emissions and depending on the temporal granularity of the assessment and boundary definitions adopted for exported renewable electricity.

Regarding the calculation procedures to assess the energy performance of a building, thanks to the decisional freedom provided by the EPBD, there is currently significant flexibility. Moving from monthly steady procedures to sub-hourly dynamic ones, the results can face non-negligible variations.

Consequently, HVAC performance assessment becomes a significant methodological node for ZeB studies.

1.1 State of the art and aim of the research

Focusing on the methods to assess the energy performance of buildings, it is possible to group them into two groups, considering the target: methods to assess the energy need, and methods to assess the performance of HVAC systems. Regarding the first category, simplified methods are widely used in Europe. In particular, the quasi-steady-state and simplified dynamic methods presented in EN ISO 52016-1 [2] have been thoroughly analysed in recent years [3]. These methods are based on monthly or simplified hourly balances with averaged boundary conditions and offer standardisation and replicability. However, they may struggle in low-energy buildings, where transient phenomena and control effects become decisive [4]. Dynamic simulation tools such as EnergyPlus, TRNSYS, and IDA ICE, model time-dependent interactions among weather, occupancy, and HVAC operation with higher fidelity [5]. They are therefore widely used for retrofit optimisation, indoor environmental quality studies, and cost-optimal analyses [6]. Their reliability, however, depends on careful calibration and consistent assumptions. Calibration frameworks rooted in established methodological work and embedded in guidelines (e.g., ASHRAE) help reduce discrepancies when benchmarking against monitored data [7]. Beyond energy needs, the representation of technical building systems (TBSs) remains a significant source of uncertainty in energy performance assessments. This is because simplified methods often oversimplify part-load behaviour, setpoint control, and component interactions into aggregated efficiencies. For hydronic systems, comparative studies show that simplified approaches, such as the ones presented in the EN 15316 technical standards series, can diverge from detailed calculations when control logic and operating conditions are explicitly modelled [8]. Similar sensitivities affect generation performance. Seasonal efficiencies derived from standardised conditions may not fully capture real operation under variable loads and temperatures, thereby increasing the uncertainty in the results. At the system level, stratification and control choices can propagate across subsystems, altering the balance of delivered heat/cool and system losses [9]. Evidence from empirical comparisons also suggests that simplified formulations may not consistently reproduce actual control behaviour for commonly used components, which can bias the partition of energy use across system stages [10]. Overall, while simplified procedures are essential for regulatory applicability, the literature indicates that methodological choices in TBS modelling can materially influence calculated efficiencies and, consequently, compliance conclusions.

This work aims to analyse the effect of different procedures to assess the energy performance of TBSs from the perspective of achieving a ZeB. The analysis, based on a case study approach, considers an office building representative of the Italian building stock, highlighting the variation in energy consumption and target achievement related to different assessment methods.

2 Methods

2.1 Whole building energy assessment procedures

Simulation methodologies for TBSs are often grouped into three broad categories [11]. Fully dynamic approaches solve detailed differential equations with very small time steps (typically minutes), allowing control cycling (e.g., thermostats and humidistats) and transient equipment responses to be represented explicitly. They provide the most accurate description of system behaviour and demand variability, but at high computational cost. Detailed heat and mass balance methods generally apply quasi-steady energy and mass balance equations at an hourly resolution to individual components such as coils, boilers, chillers, fans, and pumps; depending on the available data, they can range from detailed component-characteristic models to simplified empirical relations, offering a good balance between accuracy and effort. Quasi-dynamic methods, by contrast, assume fixed design operating conditions (for instance, constant leaving air temperatures) and do not recompute balances at each step; they can approximate overall heating and cooling loads when systems are properly sized, but may become unreliable under significant oversizing or undersizing.

Table 1. Building energy performance models analysed.

Object	Procedure		
	Monthly simplified	**Hourly simplified**	**Hourly detailed**
Energy need	Quasi-steady-state [12]	-	Dynamic detailed [13]
Emission subsystem performance (fan coil)	Efficiency correction coefficients [14, 15]	Temperature correction coefficients [16]	Component behaviour [13]
Heating and DHW generation performance (heat pump)	Rated performance points [14]	Rated performance points [17]	Performance curves [13]
Cooling generation performance (chiller)	Rated performance points [15]	Carnot-corrected EER method [18]	Performance curves [19]
Electricity generation (PV)	Whole performance coefficient [20]	Whole performance coefficient [20]	Simplified PV performance model [21]

In this work, the focus is on the analysis of a group of HVAC systems with a specific focus on the generation and emission sub-systems. The analysed methods are presented in Table 1.

2.2 Comparison workflow

The workflow, as presented in Figure 1, starts with the definition of the minimum NZEB building configuration according to the Italian legislation. This is defined as the building with energy performance equal to or lower than the reference building. This latter is a building with the same geometric features as the real building, with fixed performance for the envelope and TBSs. In particular, for the systems, constant performance values are presented for the generators, while a constant correction coefficient is provided for the other subsystems (emission, control, and distribution considered as a whole), differentiating between services.

While maintaining the same building envelope and use as the NZEB building, the performance of the systems is enhanced to reach a 10% reduction of the total primary energy required for the zero-emission building. The PV system nominal power is designed to comply with both the minimum required by Italian law and the minimum renewable energy ratio (RER) of 60% for the required services (both DHW alone and heating, cooling, and DHW together) [22]. This procedure is performed using monthly simplified methods, presented in Table I, as prescribed by the Italian law [23] to determine the building ZeB configuration to be used for the following analyses.

The building envelope and systems features are then modelled in EnergyPlus to assess with an hourly dynamic procedure the energy need for heating, cooling, and DHW. The building systems are then modelled with standard monthly, standard hourly, and detailed procedures (Table I). The results are then compared considering the single subsystems' performance, as well as considering them together.

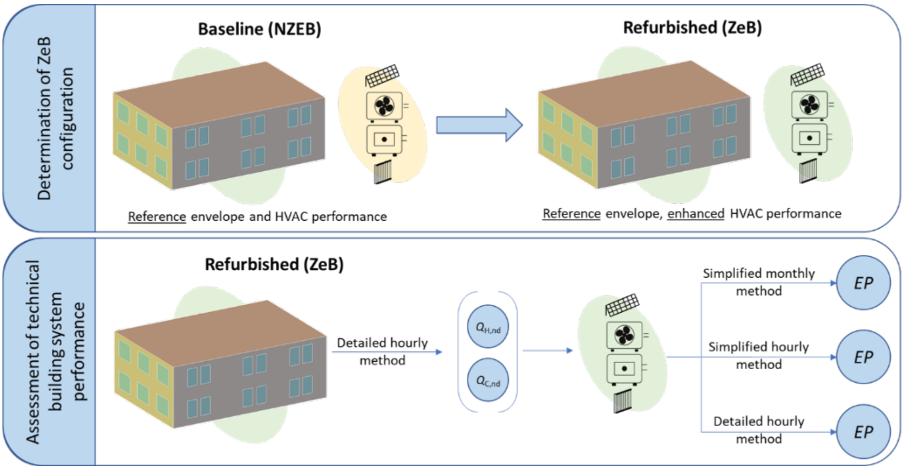

Fig. 1. Comparison workflow.

3 Application

In this section, the base case study is presented along with the description of the consistency options used to align the input data for the different procedures for the assessment of the building energy performance.

3.1 Case study

The case study is an office building representative of the Italian building stock. The building, located in Milan (*HDD* = 2404 °C·d), has two storeys with a total net floor of 363 m^2, and a gross volume of 1339 m^3. The plan is presented in Figure 2.

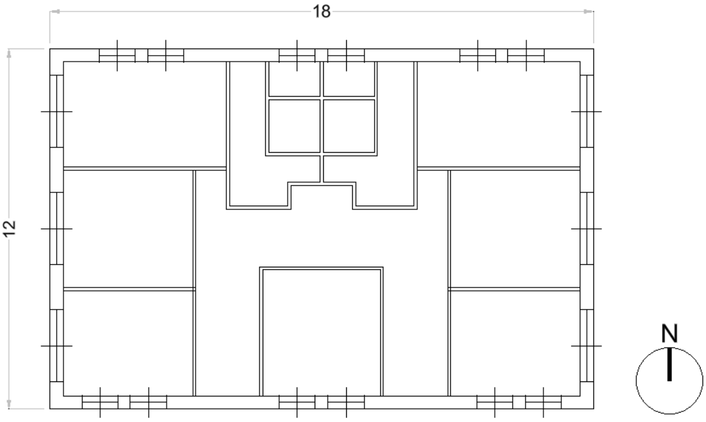

Fig. 2. Typical building floor plan.

The building, whose original state was determined from the TABULA project [24], was considered as refurbished to meet the current Zero-emission targets for buildings. Following the current prescription [1], the NZEB was used as the baseline for determining the ZeB features. The building was assumed to have the minimum envelope properties currently required to reach the NZEB level in Italy. The opaque thermal transmittance represents the mean value accounting for the effect of the thermal bridges. Those properties are presented in Table 2.

Table 2. Main properties of the building components.

Component	**Area [m^2]**	**Thermal transmittance [W·m^{-2}K^{-1}]**	**Thickness [m]**	**Areal internal heat capacity [kJ·m^{-2}K^{-1}]**
External wall (North/South)	166	0.293	0.52	440.3
External wall (East/West)	91	0.296	0.52	440.3
Roof	216	0.210	0.43	385.0
Floor	216	0.520	0.53	1000.0
Window	116	1.400	-	-

The refurbished building has a heat pump for heating and DHW, a chiller for cooling, and a PV system for electricity production. The spaces are provided with fan coils as thermal emitters for heating and cooling.

The HVAC systems are sized as a function of the required energy need, while the PV system was designed to guarantee the minimum RER in the ZeB configuration with a minimum power of 10.8 kW as defined by the Italian law [22].

The building has natural ventilation and standard use profiles, as described in EN 16798-1 [25].

3.2 Consistency options

The different methods analysed in this work, due to differences in both time-step and input complexity, needed adjustments and tuning to minimise the errors and highlight the variation of the results connected to the procedures.

In particular:

- All the occupancy, set-point, use profiles, as well as the climatic data, were defined on an hourly basis. The values for the monthly application were directly derived from them.
- The efficiency curves for the HVAC systems, used in the detailed simulation, were derived from a finite number of performance points. Those describe performance and maximum output as a function of the boundary conditions. The monthly values were derived from those points, considering mean monthly temperatures and load values.
- The electricity generated by the PV system is allocated to the building systems' electric end-uses. The PV energy share attributed to each subsystem is proportional to its electricity consumption related to the total building electricity consumption.

4 Application

In this section, the results of the determination of the ZeB configuration and of the procedures comparison are presented. The analysed cases are labelled as presented in Table 3.

Table 3. Building energy performance models analysed.

Simulation	**Procedures**					
	Energy needs for heating and cooling			**HVAC performance assessment**		
	Monthly simplified	**Hourly simplified**	**Hourly detailed**	**Monthly simplified**	**Hourly simplified**	**Hourly detailed**
$NZEB_m$	X	-	-	X	-	-
ZeB_m	X	-	-	X	-	-
$NZEB_h$	-	-	X	X	-	-
ZeB_h	-	-	X	X	-	-
ZeB_{EN}	-	-	X	-	X	-
ZeB_{E+}	-	-	X	-	-	X

4.1 Determination of ZeB configuration

As described in section 2.2, starting from the envelope with the minimum allowed performance required for an NZEB, the performance of HVAC systems was improved to guarantee a minimum 10% reduction of the EP_{gl} and a RER of 60% for the DHW service and for heating, cooling and DHW considered together.

The resulting systems exhibit the following properties. The heat pump for heating and DHW has a COP of 4.5 and a nominal power of 24.2 kW. The chiller has an EER of 4 and a nominal power of 27.2 kW. The PV system has a peak power of 14.6 kW.

The results in terms of performance indicators of the two configurations are presented in Table 4.

Table 4. NZEB$_\mathrm{m}$ and ZeB$_\mathrm{m}$ performance indicators (ZeB determination).

Service	**Symbol**	**Non-renewable [kWh·m^{-2}]**		**Renewable [kWh·m^{-2}]**		**Total [kWh·m^{-2}]**	
		NZEB$_\mathrm{m}$	ZeB$_\mathrm{m}$	NZEB$_\mathrm{m}$	ZeB$_\mathrm{m}$	NZEB$_\mathrm{m}$	ZeB$_\mathrm{m}$
Heating	EP_H	17.6	12.5	31.9	32.1	49.4	44.6
Cooling	EP_C	14.7	7.6	15.8	12.2	30.5	19.8
DHW	EP_W	0.8	0.9	2.0	2.8	2.7	3.6
Lighting	EP_L	47.6	43.0	41.6	42.9	89.3	85.9
Overall	EP_gl	80.7	64.0	91.3	89.9	171.9	153.9

4.2 Systems performance

The building, as defined in the previous section, was then reassessed with different methods. While assessing the energy need with hourly procedures, the systems were analysed with monthly, hourly simplified, and detailed procedures as presented in Table 1.

The building was at first simulated using detailed assessment procedures to determine the energy need for heating and cooling, and performing the systems assessment with the monthly simplified procedures. The reference system performance, equal to the NZEB configuration used in section 4.1 was also assessed. The results, presented in Table 5, show a reduction in the EP_H and an increase in the EP_C, consistent with the literature. The total primary energy reduction between ZeB$_\mathrm{h}$ and NZEB$_\mathrm{h}$ increases from the original 10% to 14%.

Table 5. NZEB$_\mathrm{h}$ and ZeB$_\mathrm{h}$ performance indicators.

Service	**Symbol**	**Non-renewable [kWh·m^{-2}]**		**Renewable [kWh·m^{-2}]**		**Total [kWh·m^{-2}]**	
		NZEB$_\mathrm{h}$	ZeB$_\mathrm{h}$	NZEB$_\mathrm{h}$	ZeB$_\mathrm{h}$	NZEB$_\mathrm{h}$	ZeB$_\mathrm{h}$
Heating	EP_H	11.0	7.8	21.9	22.0	32.9	29.8
Cooling	EP_C	19.7	9.5	19.1	13.7	38.8	23.2
DHW	EP_W	0.9	1.0	2.1	2.9	3.0	3.9
Lighting	EP_L	50.8	44.0	40.8	42.6	91.5	86.6
Overall	EP_gl	82.4	62.3	84.0	81.2	166.3	143.5

In Table 6, the emission subsystem thermal energy losses for the heating and cooling services are presented. Due to the assessment procedure defined by law for the NZEB$_\mathrm{h}$, it is not possible to separate the emission losses from the control and distribution ones. Therefore, those emission losses present a non-negligible overestimation that hinders the comparison with the other methods. The results show a significant variation between the assessed methods.

Table 6. Emission subsystem losses for the assessed cases.

Service	**Emission subsystem losses [kWh·m^{-2}]**			
	NZEB$_\mathrm{h}$	ZeB$_\mathrm{h}$	ZeB$_\mathrm{EN}$	ZeB$_\mathrm{E+}$
Heating	4.7	1.5	6.9	4.6
Cooling	11.6	5.4	5.9	12.7

Table 7 summarises the results of the different assessment approaches by aggregating services sharing the same generation systems and by distinguishing non-renewable, renewable, and total primary energy indicators.

While the monthly approach confirms compliance with the zero-emission target, the hourly simplified and detailed procedures show lower but comparable overall indicators.

Although differences in EP_{gl} are limited, the distribution among services and between renewable and non-renewable contributions varies significantly.

For heating and DHW, hourly approaches result in lower non-renewable primary energy values, reflecting a more realistic representation of heat pump operation under variable load and temperature conditions. At the same time, the associated renewable share is reduced, mainly due to differences in PV electricity allocation and self-consumption assumptions. Conversely, cooling primary energy indicators increase when hourly methods are adopted, due to the explicit modelling of part-load operation and outdoor temperature effects on chiller performance.

Lighting shows smaller absolute variations, but still reflects changes in PV allocation, confirming that interactions among subsystems play a non-negligible role in high-performance buildings.

All the considered cases show a reduction in primary energy from the corresponding NZEB building above the required threshold, varying from −14% to −17%.

Table 7. Emission subsystem losses for the assessed cases.

Performance indicator	**Case**	**Service**			
		Heating + DHW (EP_{HW})	**Cooling** (EP_{C})	**Lighting** (EP_{L})	**Overall** (EP_{gl})
Non-renewable [kWh·m^{-2}]	NZEB$_{\text{h}}$	11.9	19.7	50.8	82.4
	ZeB$_{\text{h}}$	8.7	9.5	44.0	62.3
	ZeB$_{\text{EN}}$	19.6	9.5	58.4	87.5
	ZeB$_{\text{E+}}$	9.3	14.1	59.4	82.8
Renewable [kWh·m^{-2}]	NZEB$_{\text{h}}$	24.1	19.1	40.8	84.0
	ZeB$_{\text{h}}$	24.9	13.7	42.6	81.2
	ZeB$_{\text{EN}}$	5.8	7.6	38.7	52.2
	ZeB$_{\text{E+}}$	3.0	14.2	38.4	55.6
Total [kWh·m^{-2}]	NZEB$_{\text{h}}$	36.0	38.8	91.5	166.3
	ZeB$_{\text{h}}$	33.7	23.2	86.6	143.5
	ZeB$_{\text{EN}}$	25.5	17.1	97.1	139.7
	ZeB$_{\text{E+}}$	12.2	28.3	97.8	138.3

5 Conclusions

This work analysed the impact of different calculation procedures for assessing the performance of technical building systems in the context of zero-emission buildings, using a representative Italian office building as a case study. Starting from the mandatory national monthly methodology, the analysis extended to hourly simplified and hourly detailed approaches, maintaining consistent boundary conditions and input data.

The results show that, when hourly-based methods are applied, noticeable differences emerge in the calculated performance of HVAC systems, particularly for generation subsystems operating under variable loads and boundary conditions. These differences affect both the magnitude of primary energy indicators and the balance between renewable and non-renewable contributions.

The margin of compliance with zero-emission targets depends on the assessment method, especially when the building operates near threshold values. As the energy demand decreases, the influence of system modelling assumptions, control strategies, and renewable energy allocation becomes increasingly significant. Nonetheless, the results show that adopting simplified methods may be conservative, tending to produce a larger calculated improvement, therefore increasing the likelihood of compliance. However, this conservatism may also lead to oversizing, with potentially unnecessary additional costs.

These findings highlight the need for greater consistency between simplified and hourly calculation procedures, especially in the context of the EPBD implementation. While simplified methods remain appropriate for compliance purposes, hourly-based assessments provide a more robust representation of real operating conditions and are essential for design verification and performance optimisation. Future developments of national and European calculation frameworks should therefore aim to reduce methodological gaps, ensuring that zero-emission targets are both formally compliant and technically robust.

Symbology

Symbols	
COP	Coefficient of performance, -
EER	Energy efficiency ratio, -
EP	Energy performance indicator, kWh·m^{-2}
HDD	Heating Degree Days, °C·d

Acronyms	
DHW	Domestic Hot Water
EPBD	Energy Performance of Buildings Directive
GHG	Greenhouse Gas
HVAC	Heating Ventilation Air Conditioning
NZEB	Nearly-Zero Energy Building
PV	Photovoltaic System
RER	Renewable Energy Ratio
TBS	Technical Building System
ZeB	Zero-emission Building

Subscripts	
C	Cooling
gl	Overall
H	Heating
HW	Heating and DHW
L	Lighting
W	DHW

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