The Role of Dynamic Primary Energy Factors (PEFs) in Building Performance Assessment: A Case Study

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Abstract

The adoption of primary energy factors (PEFs) is very common in the building sector since primary energy is one of the main metrics for evaluating the energy performance of a building. The use of such factors is extensive in European and international legislative contexts to establish a regulatory framework for enhancing building energy efficiency policies. This study analyses how the use of dynamic PEFs, variable on an hourly basis, affects the assessment of building performance. The dynamic primary energy factor for electricity has been evaluated for the Italian scenario during the year 2022, applying the methodology outlined in the EN 17423:2020 standard with an hourly detail. The conversion factor was subsequently applied to the electricity demand of a reference building for residential use. The result obtained has been compared with the same evaluations carried out using the static conversion factors currently adopted by the legislation in force, showing that there is an urgent need for adjustment. The dynamically assessed total PEF stopped at an average value of 1.84, in contrast to the 2.42 used in current legislation. As a result, the total primary energy demand of a reference building decreases by 23.07%, also involving an alteration of the ratio of renewable to non-renewable share. The study concludes that the use of dynamic PEFs is essential for both the design of new buildings and the assessment of existing buildings, especially when time-dependent HVAC, renewable energy and control strategies are considered. It also allows for better energy flow management within buildings. Finally, the study emphasizes that up-to-date PEFs are crucial for improving the energy efficiency of buildings and guiding the future decarbonization of the building stock.

1. Introduction

Primary energy represents a fundamental metric in the field of building performance, accounting for all energy inputs from the initial raw fuel sources to the final delivered energy services. This measure is of critical importance in evaluating the energy performance of buildings, understanding their environmental impact, and ensuring compliance with evolving energy policies. The assessment of primary energy consumption not only facilitates a comprehensive understanding of a building's energy demand but also aids in the comparative analysis of energy performance across different buildings. Within this topic, the significance of primary energy conversion factors (PEFs) is evident. These factors quantify the efficiency of converting primary energy sources into secondary energy carriers (Costantino et al., 2023). They play a double role: they provide a realistic measure of the energy performance of buildings and influence the perceived competitiveness of various energy technologies in the market. However, the use of primary energy factors (PEFs) has been the subject of debate, with numerous studies suggesting that they may obscure the true energy performance of buildings. This is because PEFs can vary significantly between regions and over time, reflecting the changing efficiency of energy conversion technologies and the political landscape (Bilardo et al., 2022; Baralas et al., 2023). Consequently, while PEFs are currently employed in energy performance calculations mandated by policies, there is a necessity to continue to explore their nature and their ongoing evolution, so that they can be more aligned with the objectives of reducing energy demand and promoting energy efficiency.

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Pernigotto, G., Ballarini, I., Patuzzi, F., Prada, A., Corrado, V., & Gasparella, A. (Eds.). 2025. Building simulation applications BSA 2024. bu,press.
https://doi.org/10.13124/9788860462022

1.1 Motivation of the Work

In recent decades, building performance assessment has transitioned from relying solely on static evaluations of energy supply and demand to accepting dynamic analysis. This shift is crucial not just for researchers but also for designers, as it enables a more accurate estimation of energy requirements of buildings that are highly interlinked with the energy networks and works as both producers and consumers of various forms of energy at different times (Bilardo et al., 2021). While dynamic building performance assessment has become widely accepted and practiced, a significant gap persists in its application to primary energy considerations.

Historically, the focus of dynamic analysis has been on final energy aspects, often overlooking the complexities associated with the energy supply and the primary energy. This oversight is evident in the prevalent use of static conversion factors to translate final energy into primary energy. To achieve a comprehensive understanding of building performance, it is essential to extend the dynamic approach, commonly applied to final energy, to primary energy requirements. This can be fulfilled by employing dynamic conversion factors (Noussan et al., 2018; Marrasso et al., 2019) that accurately reflect the energy flows utilized within buildings. By doing so, it is possible to enhance the precision and relevance of building performance assessments, providing the opportunity for the next generation of decision-making processes in future building design and operation.

Another crucial aspect of evaluating the performance of buildings in terms of primary energy is the electrification process, which is being supported by regulations, directives, and laws in many countries around the world. The transition towards an increasingly electrified building system is one of the primary solutions currently being pursued to mitigate fossil fuels and support decarbonization. The electric energy carrier, whose use in the construction sector is set to increase significantly in the coming years, is however highly variable, both in terms of generation and use. The strong penetration of renewable sources and the increase in variable electrical loads inside buildings (for example, electricity-based air conditioning systems) make this vector highly sensitive to the time factor. Therefore, the importance of dynamically evaluating coherent and reliable conversion factors of this specific vector takes on particular relevance in the performance assessment procedure.

Current advancements suggest that tools and methodologies for dynamic evaluation of primary energy conversion factors are readily accessible. Transmission System Operators (TSOs) and institutional databases, such as eGrid for the US and entso-e for the EU, provide public and frequent updates on electricity flows. Furthermore, regulatory initiatives, exemplified by the European standard EN 17423:2020 (CEN, 2020), emphasize the determination and reporting of Primary Energy Factors (PEF) and CO_2 emission coefficients through a defined framework that can be replicated in different contexts.

The motivations behind the development of this work can be summarized as follows:

- The use of static and dated conversion factors fails to align with the actual behavior of buildings and the significant efforts made towards a sustainable energy transition.
- The electric energy carrier, a key player in the decarbonization of the building sector, exhibits highly dynamic generation and use trends.
- To overcome the historical discrepancy between design and operation performance, and to optimize energy flows within buildings, it is imperative to consider the dynamics of the energy sources employed.

1.2 Objectives and Paper Structure

The objective of this paper is to demonstrate the importance of dynamic primary energy conversion factors for the energy assessment of buildings. In order to achieve this, the following aspects will be addressed:

- Emphasizing the importance of utilizing dynamic primary energy conversion factors for accurate and relevant energy assessments of buildings.
- Conducting a comparative analysis between traditional evaluation methods, based on static conversion factors, and the proposed dynamic evaluation method, highlighting their respec-

tive advantages and limitations within the context of the Italian regulatory framework.
- Exploring detailed analysis on primary energy flows within buildings to inform future optimization and regulation strategies.

In order to achieve these objectives, Section 2 details the materials and methods utilized for the analysis. A dynamic primary energy assessment is conducted for a reference building in Italy that is fully electric, examining scenarios with and without on-site renewable energy generation. Section 3 presents the results of the study, offering a comparative analysis with traditional evaluation methods currently mandated by the Italian regulatory framework, which rely on static conversion factors (Section 3.1). Furthermore, the potential and adaptability of the proposed dynamic evaluation method are highlighted (Section 3.2). The insights derived from this analysis will support new guidelines and recommendations for future energy performance assessments of buildings, as discussed in Section 4.

2. Material and Methods

2.1 Methodological Framework for Dynamic Primary Energy Assessment

The methodological framework employed to assess the energy performance of the building utilizes the source energy balance as the principal assessment tool. The application of the source energy balance requires the identification of primary energy conversion factors, which are necessary for the calculation of numerical operations between different energy flows. Furthermore, the proposed method aims to guarantee a resolution of the balance on an hourly basis. This is achieved by evaluating the energy flows involved and the conversion factors in consistency with the chosen analysis timestep (Bilardo et al., 2024). Eq.1 provides a mathematical expression of the source energy balance that reflects all the elements involved in the assessment:

$$E_{bal,P}(t) = \sum_i E_{exp,i}(t) \cdot f_{P,i}(t) - \sum_j E_{imp,j}(t) \cdot f_{P,j}(t) \qquad (1)$$

where:
- $E_{exp,i}$ and $E_{imp,j}$ represent the i-th and j-th exported and imported energy flows within the physical source boundary, respectively.
- $f_{P,i}$ and $f_{P,j}$ represent the primary energy conversion factor of the i-th and the j-th energy flow.

The dynamic resolution of the balance will be carried out on an hourly basis for an entire year, identified by the time variable t = 1 to 8760.

The methodology employed in this study involves two key variables: energy flows and conversion factors. These variables can be sourced from various methods, including monitoring campaigns, numerical simulations, or standardized regulatory schemes. Regardless of their origin, it is crucial that both energy flows and conversion factors share a consistent analysis timeframe that aligns with the realistic dynamic evolution of the building entity.

Fig. 1 delineates the boundaries of the source energy flow, including both on-site renewable generation systems and conversion systems. As a convention adopted in this paper, the positive results of the energy balance represent an export from the building to the external grid. Conversely, a negative balance describes an energy import from the grid to the building.

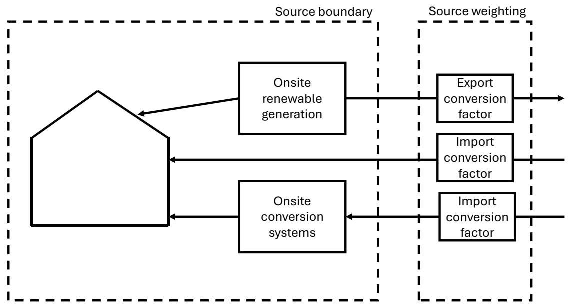

Fig. 1 – Source energy balance boundary – generic

2.2 Case Study and Methodological Choices

The proposed methodology was applied to a specific Italian case study—a medium-sized, fully electric residential building situated in Bolzano province. The case study of an all-electric building with onsite renewable self-production systems is of particular interest for two reasons. Firstly, the electricity carrier is very sensitive to variations in primary energy. Secondly, the decarbonization process required by the recent Energy Performance of Building Directive (EPBD) relies on a strong electrification of the building stock (European Parliament, 2024). This building features a maximum power meter of 6 kW and is equipped with a 9 kWp photovoltaic (PV) system installed on its roof.

The energy flows for this case study were determined using the following approaches:

- Total electricity demand was derived from statistical monitoring data provided by the Italian regulatory authority for energy networks and the environment (ARERA, 2023). Specifically, average hourly electricity consumption for a residential user accessing the free energy market in 2022 within the province of Bolzano was selected.
- The average hourly output of the PV system was simulated using the PVGIS tool. This simulation considered a 9 kWp system with a fixed slope angle of 40° facing south, also estimating system losses at 14%.

In terms of primary energy conversion factors, the following selections were made. The conversion factor applied to weigh the electricity exported to the grid utilized the avoided burden approach. This approach assumes that exported energy has an equivalent impact, in terms of primary energy, as imported energy, thus employing the same conversion factor for both flows. Furthermore, the conversion factor associated with energy exports is considered fully renewable. The conversion factor used to weigh the electricity imported from the grid was determined by applying the standard EN 17423:2020. This involved utilizing energy flow data related to the generation, import, and export of the Italian national electricity system, made available by the Italian Transmission System Operator (TSO) Terna (Terna, 2021). The application of this standard facilitated the derivation of the hourly dynamic trends for renewable and non-renewable shares of the conversion factor into primary energy for the electricity vector, as evaluated using Eq. 2 and 3.

$$f_{p,nren,el} = \frac{\sum_j (E_{in,el,j}) f_{p,nren,in,el,j} - \sum_j (E_{exp,el,j}) f_{p,nren,exp,el,j} + \sum_j (E_{pr,el,j}) f_{p,nren,pr,el,j}}{E_{del,el}} \quad (2)$$

$$f_{p,ren,el} = \frac{\sum_j (E_{in,el,j}) f_{p,ren,in,el,j} - \sum_j (E_{exp,el,j}) f_{p,ren,exp,el,j} + \sum_j (E_{pr,el,j}) f_{p,ren,pr,el,j}}{E_{del,el}} \quad (3)$$

Detailed numerical procedures and the rationale behind the chosen calculations have been previously discussed in studies published by the authors (Bilardo et al., 2022, 2024). Fig. 2 provides a clear overview of how energy is managed within the context of the case study, offering insights into the various quantities involved in the source energy balance assessment. In order to better study the impact of the use of dynamic hourly conversion factors, this study also includes an initial comparison with static and outdated conversion factors.

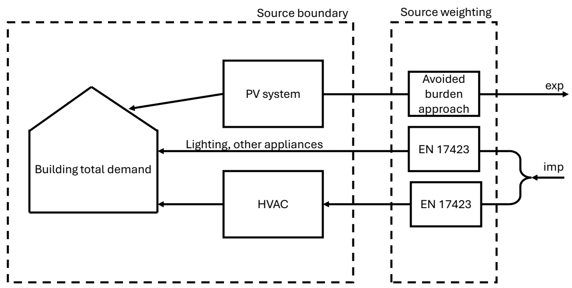

Fig. 2 – Source energy balance boundary – case study application

These static factors are defined within Italian national legislation by the inter-ministerial decree dated 26 June 2015, commonly referred to as the Minimum Requirements Decree. According to this decree, conversion values of 1.95 are assigned to the renewable share and 0.47 to the non-renewable share when converting energy flows associated with the electric energy vector.

3. Results

This section presents the results of the proposed assessment methodology, focusing on the impact of dynamic primary energy conversion factors on building performance assessment. The methodology described earlier was applied to the case study introduced in the previous section.

The initial results belong not to the building itself but to the hourly trend of the adopted conversion factors, evaluated using the standardized methodology outlined in EN 17423:2020 (CEN, 2020) applied using data from year 2022. Fig. 3 illustrates the dynamic trends of the renewable (in green) and non-renewable (in red) shares of the conversion factors associated with the electric energy carrier. The graph compares these dynamic values with the static quantities mandated by current Italian regulations, represented by the solid red and green lines.

It is evident from the comparison that the static and outdated values, proposed in 2015, significantly exceed the calculated dynamic hourly values. Specifically, the average values for the non-renewable and renewable shares stop at 1.51 and 0.34, respectively. This discrepancy highlights the advancements in energy transition policies that have enhanced the efficiency of the national electricity system in recent years. The conversion factor values depicted in Fig. 3 are crucial variables for resolving the primary energy balance of the case study building in subsequent analyses.

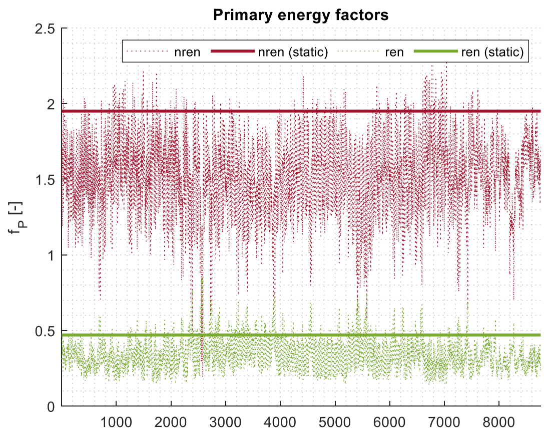

Fig. 3 – Comparison of static and dynamic values of renewable and nonrenewable primary energy conversion factors during 2022

3.1 Static Vs Dynamic Primary Energy Assessment

Assessing the primary energy demand to meet the building's need is a key indicator used within the European Union for building evaluation and classification. In this section the annual absolute value of primary energy demand has been evaluated for the year 2022, taking into account the case study building capacity for self-consumption of electricity from a photovoltaic system. This allowed for the determination of the actual electrical energy required by the building to satisfy its load. The assessment, conducted on an hourly basis, revealed a significant mismatch between energy generation and consumption for the average reference building, resulting in an annual electricity demand of 10.10 MWh (final energy in Fig. 4).

By applying both static and dynamic conversion factors, the primary energy demand was assessed in terms of its non-renewable and renewable shares. Fig. 4 presents the results of this assessment, which align with earlier considerations.

Firstly, the application of dynamic conversion factors led to a reduction in the total primary energy demand, consistent with the previously discussed values (19.70 MWh (nren) + 4.75 MWh (ren) in the static evaluation compared to 15.70 MWh (nren) + 3.11 MWh (ren) in the dynamic evaluation). However, secondly, the percentage of primary energy demand covered by renewable energy decreased from 19.4% with static factors to 16.5% with dynamic ones. This reduction makes the use of updated dynamic factors less "advantageous" but more consistent with the effective energy use of the building. This outcome is attributed to the hourly resolution of the energy balance, which prevents the renewable share from compensating for the energy demand satisfied primarily by non-renewable sources. The proposed methodology, which aligns with the dynamic evolution of building energy flows, rewards consumption profiles that align with national renewable generation patterns. However, this was not observed in the analyzed case study, underscoring the need for further optimization to fully capitalize on renewable energy sources.

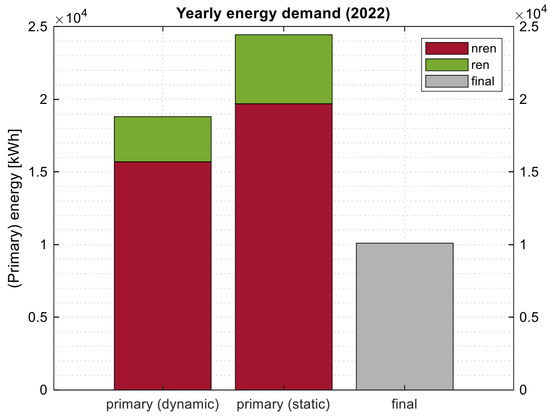

Fig. 4 – Renewable (green) and non-renewable (red) primary energy demand assessed over the course of a year on an hourly basis on the basis of final electricity demand (in grey)

3.2 Dynamic Trends for Primary Energy Flows

In order to better explore the potential and significance of a dynamic primary energy assessment, it is

therefore necessary to shift the focus to a more detailed type of analysis that better visualizes the behavior of the building on an hourly basis. This section presents a specific focus on two days of the winter and summer season taken as a reference to better describe the previous yearly aggregate results.
In Fig. 5, two represented days of the winter season have been identified, showing the development of the hourly primary energy balance using both dynamic (left in Fig. 5) and static (right in Fig. 5) conversion factors. The balance was resolved in both its renewable and non-renewable portions. For greater understanding, the hourly trends of the conversion factors (bottom of Fig. 5) are also shown, as well as the value of final electrical energy (dashed black line) before undergoing the conversion process.
From the trend of the energy balance in Fig. 5, it can be seen that the ratio of renewable to non-renewable share varies during the hours of the day in the dynamic conversion condition, while it remains constant when using static factors.
The central hours of the day, characterized by a surplus in photovoltaic production, guarantee renewable primary energy export values (positive values in the graph).

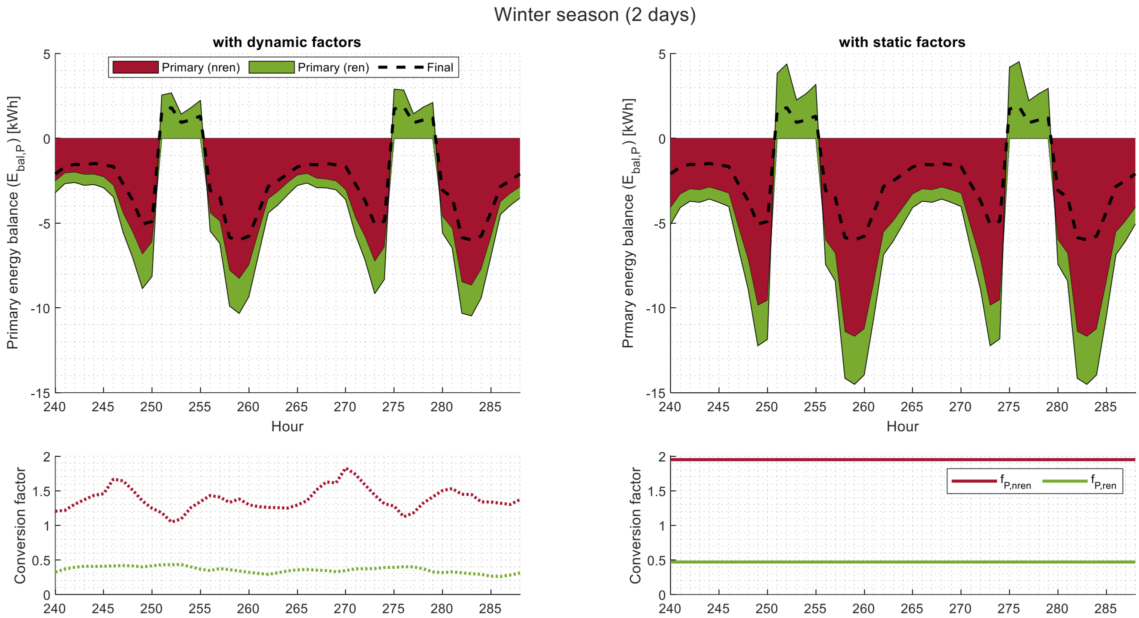

Fig. 5 – Comparison between the application of dynamic (left) and static (right) conversion factors for the dynamic evaluation of the primary energy balance – application for two days during the winter season

As it is evident, during night hours the renewable share in the dynamic case decreases due to lower renewable inputs to the national electricity grid.
A slightly different scenario is depicted in Fig. 6, where the two-day trend of the summer season is shown. Even in this scenario, while the previous considerations remain valid, a greater variability of the renewable share can be observed, demonstrated by a dynamic conversion factor that is more sensitive to daily variation (probably due to the impact of photovoltaic systems on the national system). From the trend shown in the Fig. 6, it can also be deduced that during the first day of the analysis, the building's needs could not be fully covered during the central hours of the day.
This situation, generated by a daily drop in onsite generation (due to the peculiar climatic conditions of the case study during those hours) demonstrates the effectiveness of the method in capturing possible performance variations, in line with the real behaviour of the building

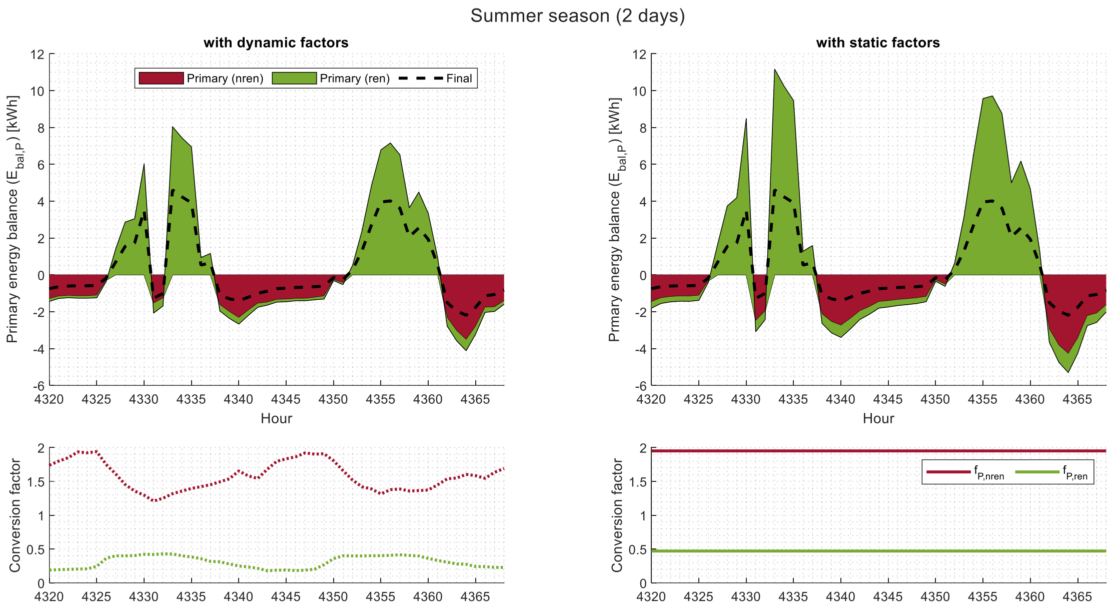

Fig. 6 – Comparison between the application of dynamic (left) and static (right) conversion factors for the dynamic evaluation of the primary energy balance – application for two days during the summer season

4. Discussion And Conclusions

This paper focused on assessing the primary energy demand for buildings, a widely recognized indicator used globally to evaluate and rank building performance. Specifically, it has explored how energy flow conversion factors into primary energy must align with the dynamic and realistic trends of energy generation and utilization within buildings. Utilizing static and outdated conversion factors fails to capture the complexity of building performance.

To address this, a dynamic evaluation method based on the primary energy balance solution was proposed, combining variable PEFs with hourly energy flows. An Italian reference case study was selected to validate the reliability of this method.

The analysis of the dynamic primary energy balance revealed the indicator's sensitivity to conversion system variability, challenging the validity of current traditional methods and highlighting the need for more dynamic approaches to building performance assessment.

The results presented in this paper offer valuable insights into understanding building performance, but they represent just one aspect of the broader picture. Many of the considerations discussed here can also be applied to assess a building's environmental impact, specifically its emissions contribution.

Evaluating a building's emissions requires the use of conversion factors, such as those for CO_2 or $CO_{2,eq}$ (Bilardo & Fabrizio, 2023). This process shares similarities with the considerations made in this study, particularly concerning the dynamic nature of emission factors. Findings of this study open the way for developing reliable, realistic, and detailed analyses of building energy performance. In this context, building performance simulation plays a key role in facilitating the adoption of dynamic PEFs. Simulation tools can easily integrate accurate and dynamic conversion factors to calculate the true energy and environmental demand of a building during a specific period of analysis. Building performance simulation also has the important responsibility of integrating a holistic evaluation process to correctly assess the optimization processes of renewable energy use, as well as more realistic advanced regulation and control systems. This is necessary in order to finally achieve an accurate process of predicting primary demand in real time.

4.1 Future Developments

Future research starting from this work will explore related topics that necessitate further investigation, such as:

- Predicting and forecasting conversion factors to generate realistic values, facilitating more resilient design approaches adaptable to future changes.

- Optimizing energy flows to minimize primary energy requirements not only during the design phase but also throughout the building's operational lifespan.

These research lines offer promising directions for advancing the field and enhancing the energy efficiency and sustainability of buildings through a more accurate evaluation of the energy exchanges of the building within the districts.

Acknowledgement

The research activity presented in this paper is done in a project funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 - Call for tender No. 1561 of 11.10.2022 of Ministero dell'Università e della Ricerca (MUR); funded by the European Union – NextGenerationEU. Award Number: Project code PE00000021, Concession Decree No. 1561 of 11.10.2022 adopted by Ministero dell'Università e della Ricerca (MUR), CUP E13C22001890001, according to attachment E of Decree No. 1561/2022, Project title "Network 4 Energy Sustainable Transition – NEST, Spoke 8".

Nomenclature

Symbols

EPBD	Energy Performance of Building Directive
PEF	Primary Energy Factor
CO_2	Carbon dioxide
E	Energy
f	Conversion factor
t	Time

Subscripts/Superscripts

P	Primary
eq	Equivalent
ren	Renewable
nren	Non-renewable
del	Delivered
el	Electricity
pr	Production
i	i-th energy flow
in	Input
j	j-th energy flow
imp	Imported quantity
exp	Exported quantity
bal	Balance quantity

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