Dynamic evaluation of the electrical primary energy factor for building energy performance: Insights from 2022 Italian data

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Dynamic evaluation of the electrical primary energy factor for building energy performance: insights from 2022 Italian data

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Abstract. The primary energy factor (PEF) represents a fundamental concept for converting a final energy carrier into primary energy. Among its many areas of application, building industry is of particular interest, since primary energy demand is a representative and widespread indicator for evaluating a building's whole energy performance. This paper starts by exploring the critical issues related to the use of PEF, which is often evaluated through outdated, static values. Through the application of one of the methods of the UNI EN 17423:2021 standard, the hourly trend of the primary energy factor for the electric carrier in Italy during the year 2022 was evaluated. Results show the strong dynamicity of the PEF and the existing relationships between its renewable and non-renewable shares, which are strongly influenced by pro-duction, import and export strategies. The obtained PEFs were applied to a case study of a residential building, evaluating the primary energy needs under different final energy conversion scenarios. This work highlights the need for an update of the PEF to dynamic values consistent with the energy context of a country to facilitate the energy transition, as well as to reduce the supply and demand mismatch, and reward the use of renewable energy.

1 Introduction

Many of the objectives set by European energy consumption reduction policies are based on the reduction of primary energy consumption. The current objective for the European Union, for example, as set out in the "Fit for 55" package, is a reduction in primary energy consumption of 40.6% compared to 2007 levels. The evaluation of the energy consumption of a building and its energy rating are determined based on an index expressed in non-renewable primary energy consumption.

Primary energy is the energy that comes from renewable and non-renewable sources that has not undergone any transformation or processing and therefore differs from the delivered energy for final consumption as it considers all the losses from transformations it can undergo. The determination of primary energy consumption is applied in different areas, especially in the building sector.

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To convert from delivered energy use to primary energy consumption, it is necessary to use the Primary Energy Factor (PEF) for each energy carrier, which indicates the amount of energy used to generate a single unit of energy delivered for final consumption [1]. The most significant energy carrier today is electricity, because electricity consumption in Italy is higher than for other forms of energy, because it can be produced in different ways and therefore associated with different PEFs, and finally because the construction sector is moving towards greater electrification of new and retrofitted buildings, at the expense of other energy carriers such as natural gas.

At the Italian level, for the electricity energy carrier, the PEF is provided by the 2015 Minimum Requirements Decree with a static value of 2.42, which can be broken down into its renewable fraction of 0.47 and its non-renewable fraction of 1.95. If we look at the European level, on the other hand, this value is currently 1.9, provided through Directive 2023/807, which supersedes the previous directive valid until the end of 2022. However, the Italian values seem outdated, as they were defined in 2015 based on data from previous years, while in the last decade, the share of renewable energy in the national energy mix has increased significantly. Additionally, these values are static, which limits the ability to exploit flexibility options and assess the impact of renewable energy sources. Therefore, more accurate and time-varying values of PEFs are needed for calculating the primary energy consumption of buildings and conducting real-time and predictive optimization.

In order to create a harmonized framework for reporting key choices made in the procedure for determining primary energy factors (PEFs) and CO_2 emission coefficients for energy delivered to and exported from buildings, the EN 17423 standard has been adopted in 2020 [2], later adopted also by UNI in 2021 [3]. This standard specifies the choices that must be made to calculate the PEF(s) and CO_2 emission coefficients related to different energy carriers, considering also the fact that PEFs and CO_2 emission coefficients for exported energy can be different from those chosen for delivered energy. The standard is primarily intended for supporting and complementing EN ISO 52000-1 [4], as the latter requires values for the PEFs and CO_2 emission coefficients to complete the EPB calculation.

The fact that PEFs calculated from real and updated data are different from the standard one adopted at normative level by each country, is demonstrated by two recent studies. In the first one, Bilardo et al. [5] demonstrated an important decrease in the primary energy factor over the last 20 years in some EU countries, from -7% in France to -32% in Denmark. Later, Balaras et al.[6] computed the PEFs for all EU countries from 1990 to 2019 and showed how PEFs vary across countries in Europe, depending on their energy mix – in countries with a higher share of renewable sources, such as Norway and Sweden, the non-renewable factor is lower. Following the general decrease trend also demonstrated by Baralas et al. [6], it can be noted how crucial will be the role of primary energy in reducing greenhouse gas emissions and achieving the European Union's climate goals.

As regards the time variability of PEFs, two interesting studies – [7] and [8] – concentrated on the Italian electricity production. In both studies, the time evolution of these two quantities is shown on an annual, monthly, and daily scale, thus increasing the temporal resolution, highlighting large temporal variations in PEFs and their reciprocal values, showing that the greatest contribution to these variations is the share of renewable sources. Although the average annual results are already significantly lower than those proposed by the Italian law, both papers stress the fact that it is necessary to carry out a dynamic evaluation of the PEF values as they are strongly dependent on the season and the hour of the day. The same can be said when one switches from static to dynamic CO_2 emission factors [9].

The introduction of the concept of transient PEFs was also reinforced by the 3rd recast of the European energy performance of building directive (EPBD), where it is said that it will be necessary to use dynamic primary energy factors for each individual energy vector in the evaluation of the energy performance of a nZEB (near Zero Emission Building) since these buildings will have to have a high flexibility of energy demand carrying out a continuous matching between energy supply and demand.

1.1 Scope of the work

Through the application of one of the methods from the UNI EN 17423:2021 standard, the hourly trend of the primary energy factor for the electric carrier in Italy during the year 2022 was evaluated. As regards the physical boundary for the PEFs calculation, considering the data availability, the whole Italian territory should be retained since more refined and local data of energy import, export and production are not available at sufficiently lower time steps. The results were analysed in order to obtain the relationship between its renewable and non-renewable shares and how such dynamic factor may be predicted for future time steps. The PEFs obtained were then applied to a case study of a residential building, evaluating the primary energy needs under different final energy conversion scenarios.

2 Materials and methods

In this paragraph all choices that have been made among those available in the UNI EN 17423 standard in order to perform the calculation of the dynamic PEF of the electricity energy carrier in Italy in 2022 are reported. Then, by exploiting the hourly statistical data of Terna, the company that operates the Italian high and very high voltage electricity transmission network, on the energy generated by energy source, on imports and exports with various European countries and on final loads, the evaluation of the hourly dynamic primary energy factor for the entire year 2022 may be made.

2.1 Definition of the Annex A of UNI EN 17423 assumptions

The physical boundary was set at the national border, in order to obtain a PEF value for all of Italy. This choice was made primarily due to the availability of data at the national level and not with regional or local distinctions.

The temporal resolution, to overcome the calculation of static PEFs, and other problems already mentioned, was set to hourly, in order to have the maximum possible resolution.

Regarding the source of the data, the statistical data collected by Terna that are used to draw up the annual reports were used. In particular, a set of historical data [10] was used that includes hourly values for the generation of electricity for all the different energy sources, hourly data on exchanges outside the national perimeter both in import and export, and hourly values of loads, that is, the amount of energy that is required for final use. All data are from the last available year online, that is 2022. Furthermore, it was decided to report the use of lower calorific value.

Where it is requested to specify the choices regarding the input data used, for the energy sources considered, all the sources from which it is possible to generate electricity in Italy were included, thus considering also the amount of self-consumed energy, as the Terna dataset also contains a specific entry that indicates this amount.

For the conversion of fossil fuels and nuclear power, the physical content method was chosen, considering the generation efficiency of non-renewable energy sources.

For the conversion of renewable energy sources, the direct equivalent method was chosen, assigning these sources a PEF of 1, which corresponds to a generation efficiency of 100%, as these forms of energy do not produce losses. Finally, for the PEF of the energy that is exported, the PEF of production of the energy carrier that is exported was used. In this way, since the geographical scope is at the national level, the PEF of national production is used.

As for the last section, which concerns the choices regarding the evaluation method, it was chosen to consider exchanges with other geographical perimeters with different PEFs, differentiating import and export. After that, since the system considered is a multi-input system, that is, it uses multiple energy sources to produce the energy carrier in output, the most commonly used method was adopted, which is the average calculation, in which the various primary energy factors of each energy source are weighted to arrive at the total PEF.

Finally, since the calculation of the PEF is related to a single energy carrier (electricity), there is no need to identify a mode of evaluation for multi-output systems. In addition, it is specified that a LCA assessment is not carried out because the amount of data needed to carry out this assessment is impossible to obtain on such a low time scale.

2.2 PEF calculations

Each PEF is obtained through the following equation:

$$f_{p,nren,el} = \frac{\sum_j (E_{in,el,j}) f_{p,nren,in,el,j} - \sum_j (E_{exp,el,j}) f_{p,nren,exp,el,j} + \sum_j (E_{pr,el,j}) f_{p,nren,pr,el,j}}{E_{del,el}} \quad (1)$$

for the non-renewable factor, and:

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

for the renewable one and where:

- *E*: indicates an energy flow of the generic energy carrier (imported – in, exported – exp or produced – pr).
- f_P: is the primary energy factor relating to the energy flow considered.
- *j*: indicates the j-th energy carrier flow considered for production (when multiples are involved).

As regards the various factors to be used in the equations (1) and (2), certain assumptions have been made in order to be able to carry out the relevant calculations.

First of all, as regards the factors concerning the energy that is imported within the geographical perimeter, coming from various European states, it was decided to exploit the values present in [11]. In this way, an evaluation was carried out that assigned the corresponding PEF value to each country that supplies energy to Italy. Since it was not possible to separate the renewable share from the non-renewable one, it was decided to make the hypothesis that the energy imported from abroad is solely of non-renewable origin.

Similarly, as regards the exports, it is not possible to divide the renewable share from the non-renewable share from the data made available by Terna. Therefore, the primary energy factor relating to exports for renewable sources was set at 0.

The PEF relating to exports of a non-renewable nature, this will have a value equal to that of electricity production at a national level.

The primary energy factor relating to the production from renewable sources, following the direct equivalent method, was set equal to 1 and it was used for all renewable sources, i.e. solar, wind, geothermal, hydroelectric and the fraction of self-consumed energy.

3 Results

Following the methodology summarized before, the hourly values for the Italian renewable and non-renewable PEFs were obtained for the entire year 2022, and then the total PEF were obtained (see Figure 1).

First, it can be observed that the average values are significantly lower than those envisaged by Italian legislation. In fact, the fp,ren,el takes on an average value of 0.34, significantly lower than the 0.47 required by the legislation. Similarly, the value of fp,nren,el has a value of 1.51 which is significantly lower than 1.95 envisaged by the Minimum Requirements Ministerial Decree of 2015. This leads to a value of the total average annual (2022) PEF for electricity of 1.85.

The main objective of this work is to compute PEFs values that can be dynamic and not static, to highlight how these are sometimes higher or lower than the values prescribed by the standard just mentioned. Analyzing the results obtained in Figure 1 that report the time evolution of the 2022 PEFs for electricity in Italy, it can be seen that they have a fairly high fluctuation, not only over the course of the year, but also within the same day.

This leaves room for the possibility of being able to carry out different analyzes from the results obtained in order to exploit the additional knowledge that arises. During the course of the year, there are very few results that exceed the limit of the legislative static total PEF. In fact, the calculated values relating to the total PEF that assume a result higher than 2.42 are only 3, equal to 0.03%.

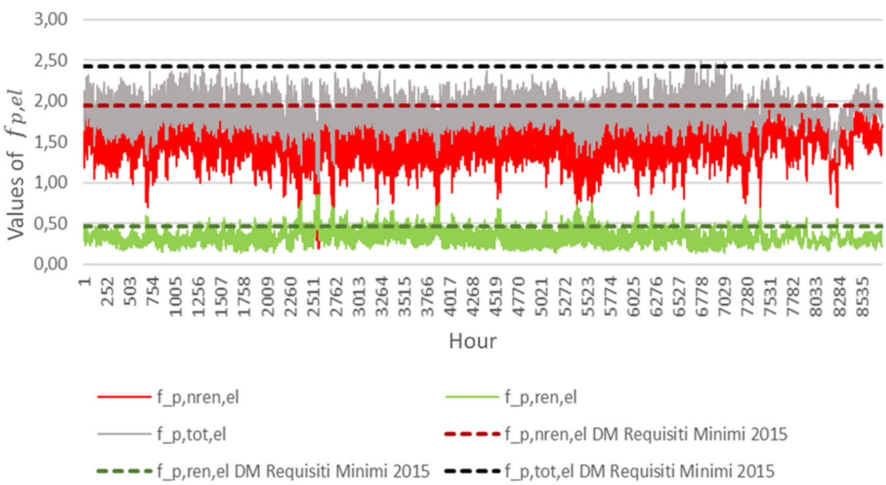

Fig. 1. Time plot of the electricity PEFs for 2022 in Italy and comparison with the static legislative values.

3.1 Frequency analysis

As can be seen from Figure 2, the two frequency distributions of renewable and non-renewable PEFs are almost totally distinct from each other. Values of the non-renewable PEF which are less than unity can be explained by the fact that, if the percentage of energy derived from renewable sources takes on very high values compared to the total production, there will be lower values of the non-renewable PEF which, in some cases may drop below 1.

It can also be noted that the non-renewable PEF values take on an almost Gaussian-shaped distribution, with the frequency distribution of each interval progressively decreasing as it moves away from the average value which is located in the interval with the highest data frequency.

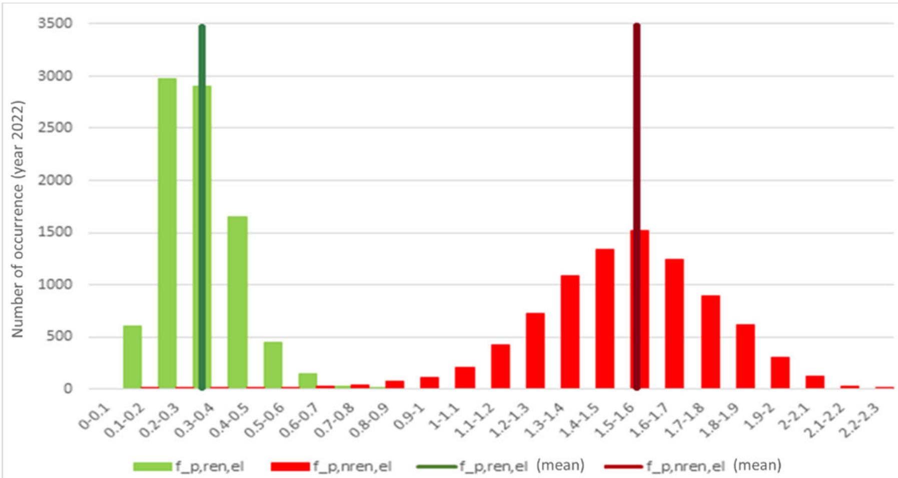

Fig. 2. Frequency analysis of the electricity renewable and non-renewable PEFs for 2022 in Italy.

3.2 Daily variation analysis

In order to understand the daily variation, the following box-plot analysis was performed and reported in Figure 3. In the box plots of the renewable (left) and non-renewable (right) PEF, the average annual value assumed by the renewable PEF for each hour of the day, the values of the 1st and 3rd quartile and the two error bars to arrive at to the minimum and maximum values assumed during the 2022 year are reported. For the non-renewable PEFs, it can be observed how the trend of the box plots over the day creates a concavity with the peak at the minimum point identified at midday; this is due to the fact that in the central hours of the day the contribution of renewable sources is greater, mainly given by the large share produced through solar photovoltaic. From 6 pm until midnight the average value assumed by the non-renewable PEF is almost constant and then progressively increases its value up to the maximum that is reached at 6 am.

Similarly, what was observed for the non-renewable PEF is reflected in the renewable one: the curve has a convexity in the central hours of the day, with a maximum at midday. As regards the other hourly values reported, it can be observed how the same constancy of the values taken in the final hours of the day but how this is also present in the first hours of the day.

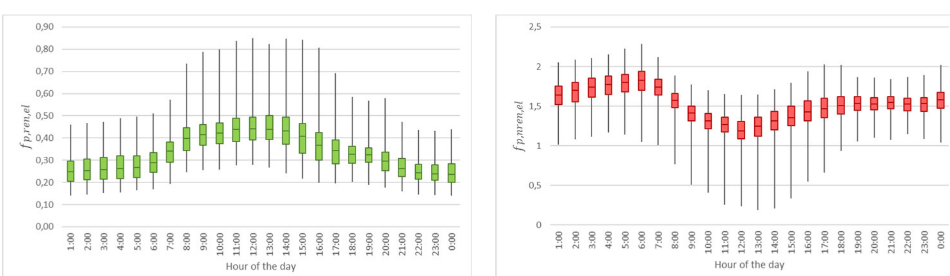

Fig. 3. Box plot of the electricity renewable and non-renewable PEFs for 2022 in Italy.

3.3 Carpet plot analysis

After having verified that there is a general correlation between the non-renewable PEF and the renewable one, it was decided to carry out a more detailed analysis by representing, through heatmaps created with the Rstudio software, the values of both PEFs for all the days of the year (Figures 4 and 5) trying to find days that could best express a correspondence between the two quantities (nren and ren) and may be studied in detail. The highest values assumed by the non-renewable PEF are found during the night hours and especially in the early hours of the morning (around 6 and 7 am) and to which correspond relatively low values of the renewable PEF. If we instead observe the maximum renewable PEF, they are reached during the central hours of the day, always due to the photovoltaic share reaching the maximum of its electrical producibility, highlighting the presence of days in which very high values of the renewable PEF are reached.

From the two graphs, this is quite evident for the days of 17 and 18 April, in which there are the highest values of the renewable PEF and the lowest values for the non-renewable PEF.

These two days correspond respectively to Easter and Easter Monday 2022. Therefore, from here on, by choosing as a reference the day of 18 April 2022 and the following working day, we will try to find a correspondence between the values assumed by the PEFs and the load profiles of the same days, made available by the data collected by Terna.

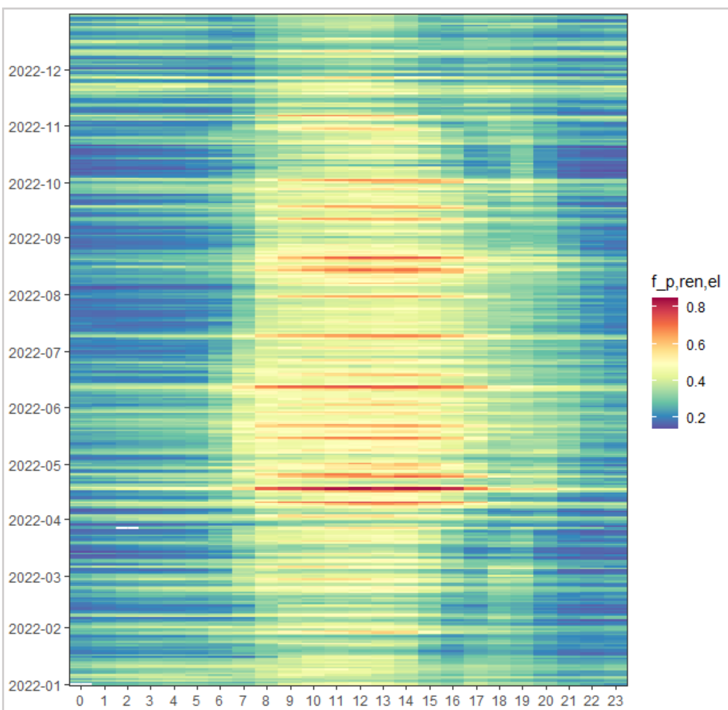

Fig. 4. Heatmap of the electricity renewable PEFs for 2022.

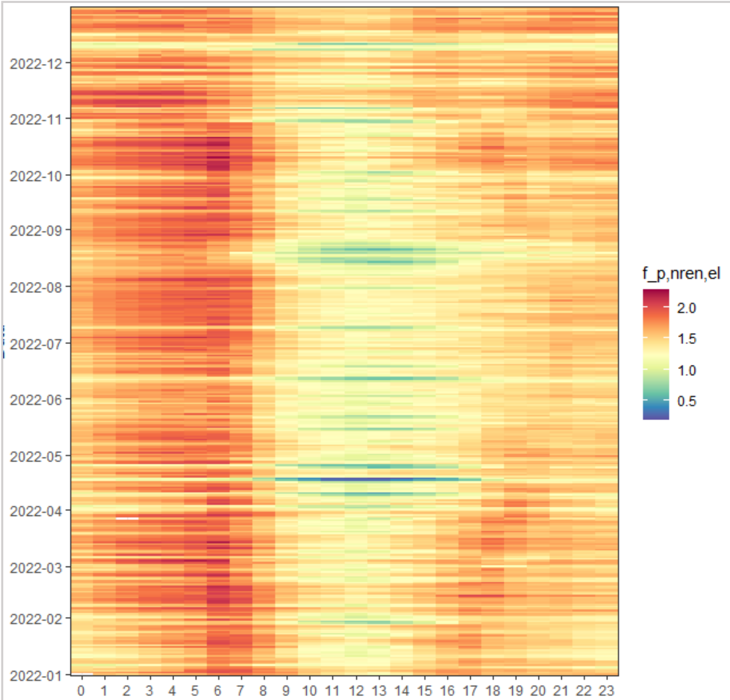

Fig. 5. Heatmap of the electricity non-renewable PEFs for 2022.

3.4 Daily profile analysis

Looking at the trends of the renewable and non-renewable PEFs during April 18 and 19 in Figure 6, completely different values and trends can be seen. In fact, taking Easter Monday into consideration (April 18), we observe how the values assumed by the load are relatively low because the production of electricity from renewable sources is able to almost completely cover the energy demand during the central hours of the day, making it necessary to have a low participation of non-renewable sources in the electricity generation process considering the very low load (Figure 7). As regards the non-renewable energy there are very low values during the central part of the day, as a large production of energy from these sources is not necessary, making the corresponding PEF value low.

However, if we observe the day of April 19th, since the values assumed by the load are higher than those of the previous day, we have clearly different PEF values.

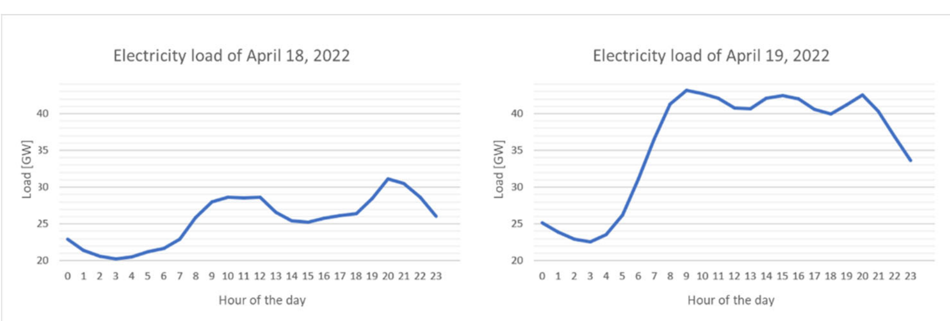

Fig. 6. Italian electricity loads of two subsequent days in April 2022.

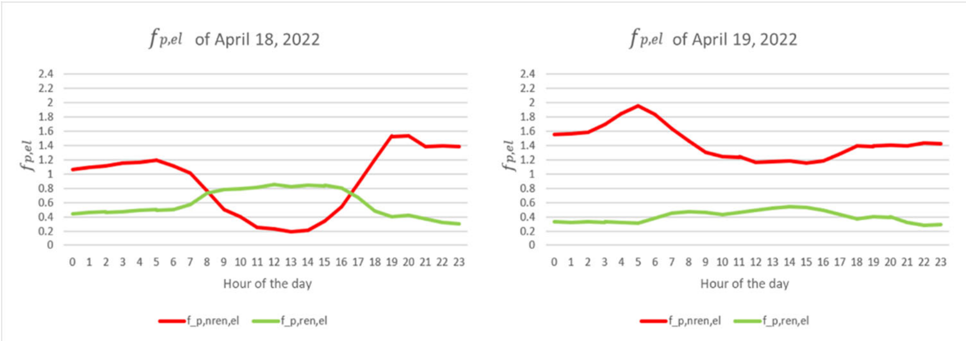

Fig. 7. Italian electricity PEFs of two subsequent days in April 2022.

In fact, during daytime hours the energy required takes on higher values, meaning that the production of renewable sources is unable to reach the same percentage of coverage as on 18 April, making it necessary to produce a large amount of energy from non-renewable sources. Consequently, a more constant renewable PEF value is observed throughout the entire day but with lower values than those of the previous day; instead, the non-renewable PEF takes on higher values, as it is responsible for the need to produce the amount of energy to fill the gap between energy produced from renewable sources and the required load.

3.5 Application to a case study

In this paragraph, the dynamic primary energy factors (PEF) calculated previously are applied to a case study, to evaluate the actual primary energy savings resulting from the use of these values instead of the static ones of the 2015 DM Requisiti Minimi. To formulate a reference building profile, the average hourly electricity load data provided by ARERA (Italian Regulatory Authority for Energy, Networks, and the Environment) for the year 2022 across diverse regions in Italy was utilized. The primary aim of this phase was to establish an hourly electricity demand profile representative of a reference Italian building. This involved applying the following assumptions and criteria:

- Selection of reference region: Piedmont was designated as the reference region for this study.
- Consumer power availability: only electrical consumers with a power demand falling within the range of 1.5 to 3 kW_e were considered. This range was chosen to emulate the electricity consumption patterns typically observed in a standard residential flat.
- Building intended use: The analysis specifically targeted continuous residential flats.
- Contract type: Only dwellings serviced by higher protection contracts, excluding open market contracts, were taken into account.

Adopting these boundary conditions, ARERA provided three distinct hourly electricity demand profiles for each month of the year: one for weekdays, another for Saturdays, and the last for Sundays. With this comprehensive dataset, the hourly load profile for an entire year was reconstructed, effectively representing the typical electricity demand of a residential household in the selected region. The final result is the yearly energy load profile reported in Figure 8. Electricity consumption is greater during the winter season and lower in the weeks of the year of the summer months.

The evaluation of the primary energy consumed by this typical building during the year was done by applying three different types of primary energy factors, obtaining the results shown in Table 1.

In the first case, the static values prescribed by the Minimum Requirements Ministerial Decree of 2015 were used, dividing the renewable fraction from the non-renewable one, with the renewable PEF equal to 0.47 and the non-renewable one of 1.95. In this case, or by following the provisions of the Italian legislation in force, a primary energy consumption is obtained which is equal to 821.4 kWh as regards that derived from renewable sources and 3407.7 kWh for that derived from non-renewable sources.

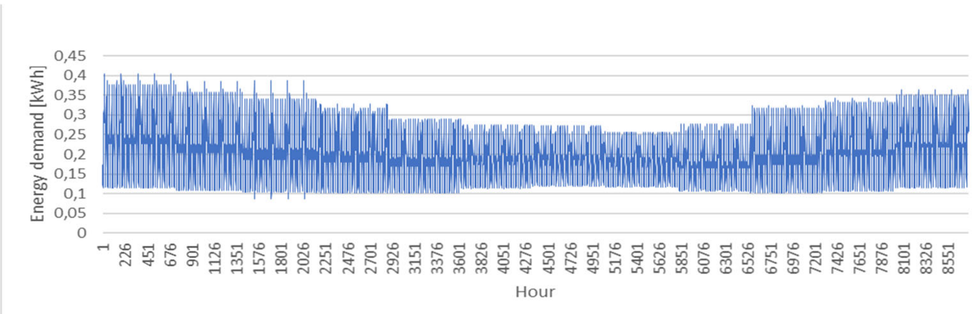

Fig. 8. Yearly electricity load profile of a typical household in Piedmont region.

Instead, using the dynamic factors calculated for 2022, as can be seen from the graph in Figure 9, we can see a trend that no longer follows that of the electricity load (Figure 8). The evaluation leads to a primary energy consumption of 595 kWh (renewable source) and of 2589.7 kWh (non-renewable source), values more than 20% lower than those calculated with the static PEFs.

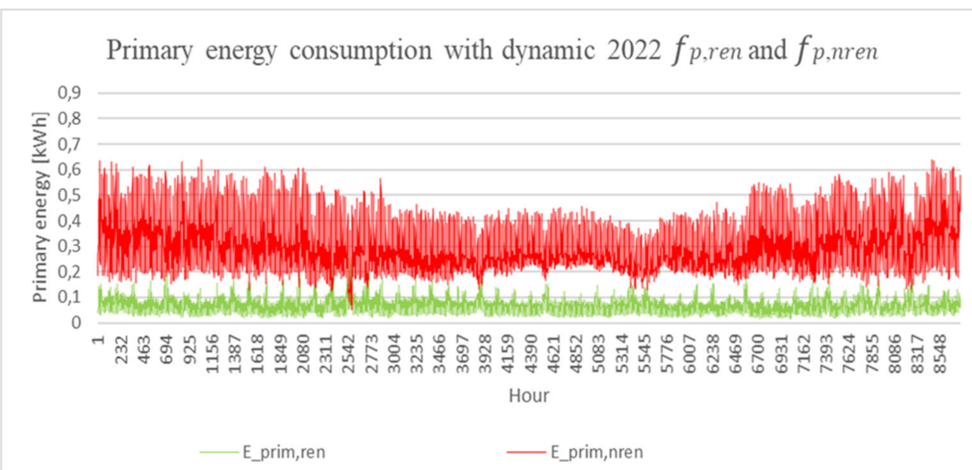

Fig. 9. Yearly primary energy consumption profiles of the case study household.

Finally, static values of the PEFs were applied, but relating to the year 2022. As can be seen from the results reported in Table 1, the values do not differ from those obtained with the application of the dynamic PEFs. Looking at the percentages of energy savings reported in Table 1, it can be seen that it is the non-renewable (n-ren) part of the factor – the one used for the energy rating in energy performance certificates – that is more sensible to the dynamics (24% of reduction in the dynamic case instead of the 22.6% in the static reduction).

Table 1. Results in terms of primary energy of the case study household with different primary energy weighting factors.

Case	Primary energy consumption [kWh]			Energy saving (ren)	Energy saving (n-ren)	Energy saving (total)
	Renewable	Non-renewable	Total			
Static 2015 DM Requisiti minimi PEF	821.4	3407.7	4229.1	-	-	-
Dynamic 2022 PEF	595.0	2589.7	3184.7	27.6 %	24.0 %	24.7 %
Static mean 2022 PEF	594.2	2638.8	3233.0	27.7 %	22.6 %	23.6 %

From these results, it may seem that as regards the overall yearly primary energy consumption, there is no substantial difference between the static evaluation compared to the dynamic one, as long as updated values are used. However, the case study investigated here, for the sake of generalization, does not present the characteristics of a prosumer, but is configured as a mere consumer of electricity. With a dynamic evaluation, one may get more correct results hour by hour, allowing not only to have an approximation of the primary energy consumed, but also of that exported or not consumed at each different time step. This is certainly important in the case of buildings that are, as defined in art. 2 of the 3rd EPBD recast, "zero emission buildings" with high flexibility of energy demand in order to contribute to the optimization of the energy system, capable of carrying out a continuous matching between energy supply and demand, in way to optimize energy consumption. Dynamic PEF values therefore allow the additional information to be exploited to carry out different considerations and actions compared to static cases on this type of buildings.

4 Conclusions

Applying the methodology proposed by the UNI EN 17423 standard, the renewable, non-renewable and total hourly PEFs of the electricity carrier for Italy in 2022 were determined. The results highlighted a discrepancy between the calculated values and the PEFs currently envisaged by Italian legislation, making clear the need for an urgent re-evaluation of these values. In fact, analysing the dynamic trend of the PEFs, an average value of 1.85 was reached, significantly lower than the value of 2.42 required by Italian legislation, it was observed that only a few values during the entire 2022 are greater than the regulatory value. Consequently, even the renewable and non-renewable fractions, which take on an average calculated value of 0.34 and 1.51, are decidedly lower than what is foreseen by the Minimum Requirements Ministerial Decree of 2015.

It can be deduced that priority should be given to updating the PEFs envisaged by the Minimum Requirements Ministerial Decree of 2015, to be replaced with new factors that are more truthful than those proposed by the legislation, as it is observed that the use of PEFs that are dated compared to those determined in the processed has a huge impact on primary energy consumption. This aspect was also pointed out by other previous works in the literature.

Then, it is clear that the concept of time-variation of PEFs cannot be neglected, as it allows the additional information deriving from this approach to further optimize and reduce the use of electricity, in accordance with what is described by the 3rd EPBD recast. The hourly dynamic analysis of PEFs is crucial to understand the daily variability of the conversion factors and to be able to implement optimization strategies aimed at minimizing the primary energy requirement of buildings.

In order to obtain time-variable PEFs, the prediction of dynamic PEFs is a strategic tool necessary for the correct design of buildings consistent with the existing energy scenario and resilient to any future scenarios and it is currently investigated by the authors.

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