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Original article

The role of Primary Energy Factors (PEF) for electricity in the evaluation and comparison of building energy performance: an investigation on European nZEBs according to EN 17423:2020

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Abstract: Evaluating the energy performance of buildings is a fundamental aspect for quantifying the impact of national energy policies supporting energy transition and sustainable development of countries. However, evaluations carried out on final energy consumption risk leading to approximate solutions that do not take into account the generation, transmission and distribution efficiency of energy systems. Furthermore, it is increasingly difficult to compare similar buildings that belong to different geographical contexts. To overcome these problems, a common solution, that is adopted at European and international level, is the use of the concept of primary energy, and the relative primary energy factor (PEF). The current assessment of primary energy for the performance of European buildings is governed by individual national laws, which are often out-to-date and not representative of current national energy systems. In this work, the recent EN 17423:2020 standard was adopted to apply a harmonized methodology in the evaluation of PEF for different European countries, considering the electricity energy vector. The results demonstrated first an important variation in the primary energy factor over the last 20 years, with decreases from -7% (in France) to -32% (in Denmark). Using this methodology, the primary energy needs of 37 European representatives nearly Zero Energy Buildings (nZEBs), located in 11 different member countries, were assessed. For the first time in literature, it was possible to compare European buildings energy performance following a standardized assessment procedure. The implications of this work represent a starting point for comparisons on the European building stock, also indicating the need for an update of national regulations regarding the assessments of the energy performance of buildings.

Keywords: Primary Energy Factor; PEF; EN 17423:2020; Building Energy Performance;

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Nomenclature and abbreviations

Nomenclature

a	Allocation factor (-)
e	Energy Expenditure coefficient (-)
E	Energy (kWh)
f	Factor (-)
η	Efficiency (-)

Acronyms

AB	Apartment Block
CHP	Combined Heat and Power
DHW	Domestic Hot Water
EED	Energy Efficiency Directive
EHPA	European Heat Pump Association
EPB	Energy Performance of Building
EPBD	Energy Performance of Building Directive
EU	European Union
HP	Heat Pump
IEA	International Energy Agency
LCA	Life Cycle Analysis
MFH	Multi Family House
NCP	Net Calorific Power
nZEB	nearly Zero Energy Building
OECD	Organization for Economic Co-operation and Development
PE	Primary Energy
PEF	Primary Energy Factor
PV	Photovoltaic
RES	Renewable Energy Sources
SFH	Single Family House
TABULA	Typology Approach for BUiLding stock energy Assessment
TH	Terraced House

Subscripts

cr	Carrier
D	Distribution
del	Delivered
el	Electricity
exp	Exported
g	Generation
H	Heating
in	Inside
nd	Need
nren	Non-renewable

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out	Output
P	Primary energy
pr	Produced
ren	Renewable
TOT	Total

1. Introduction

The European Parliament, through Regulation 2018/1999 "Energy Union and Climate Action", established that Member Countries must implement strategies aimed at achieving long-term objectives relating to greenhouse gas emissions. The European Commission plans to act on five dimensions to achieve certain objectives: energy security, internal energy market, energy efficiency, decarbonization and finally, in the field of research, innovation and competitiveness. In particular, with regard to energy efficiency, the European Regulation establishes that « Member States shall express their contribution in terms of absolute level of primary energy consumption and final energy consumption in 2020, and in 2030. […] They shall explain their underlying methodology and the conversion factors used » (European Parliament, 2018b).

Primary energy, as opposed to final energy, is a quantity that takes into account the history and origin of matter energy; in addition, primary energy is a performance indicator that allows to standardize the calculation of the environmental impact resulting from the use of different energy resources and that was widely adopted in the last twenty years in the sustainable building sector. Primary energy can be understood as "energy from renewable and non-renewable sources that has not undergone any conversion or transformation process" (European Parliament, 2018a). The concept of primary energy is therefore fundamental for comparing energy from different sources using a single numerical value (Kurnitski, 2013).

For this reason, recent recasts of European directives, such as the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD), do not only evaluate the final energy but rather the primary energy, since it considers all the energy needed in the various stages preceding the final energy supply.

The conversion of primary energy into final energy is carried out through suitable conversion factors (f_P or PEF, acronym for Primary Energy Factor). For each energy carrier, a PEF considers the necessary energy for extraction, processing, storage, transport, generation system, transmission and distribution losses of the carrier. The primary energy factor is defined by the ratio between primary energy E_P and final energy E_{del} (delivered), as reported in Equation (1):

$$f_P = \frac{E_P}{E_{del}} \left[\frac{kWh}{kWh}\right] \quad (1)$$

Factor f_P links the concept of primary energy to that of final energy, indicating how much primary energy is needed to generate a unit of final energy. Electricity, as well as thermal energy, are energy carriers that can be produced from different primary energy sources such as fossil fuels (gas, coal, etc.), nuclear energy or from renewable energy sources (hydro, wind, solar, etc.). The PEF value of these carriers is not uniquely defined at international level, nor is the procedure adopted to calculate them.

The building performance sector is relevant to the concept of primary, both because this sector is responsible for over a third of the global final energy consumption (International Energy Agency, 2019), and because buildings use various energy resources. In this context, the comparison between different buildings it would not be possible without primary energy considerations. Building energy performance can be studied by monitoring consumption or by using simulation tools, which reproduce the behavior of a building (Luddeni et al., 2018). For this reason, energy monitoring and simulations can be applied to certify and classify the performance level of a building, or to estimate its final energy needs. Although the final energy requirement is a useful indicator for understanding the performance of the building, this parameter does not assess the environmental impact resulting from the consumption of resources and emissions associated with the use of energy (Costantino et al., 2021). The final energy requirement is therefore not a good benchmark for buildings that have different energy mixes, such as buildings with in-situ PV (Tamašauskas et al., 2020) generation or with cogeneration units (CHP) (Deru & Torcellini, 2007). For this reason, the energy certifications of European buildings are mainly based on primary energy needs and the national building directives are constantly engaged in calculating adequate national PEFs (eERG-PoliMi (Energy Department), 2019).

The adoption of new technologies (for example CHP systems and renewable sources) requires an increasingly accurate and timely evaluation of the PEF. Since energy generation is the result of processes that vary in time and space, consequently also the PEF has a space-time variability that cannot be neglected. However, values of PEFs in most European countries are represented by constant numbers that reflect the historical national average. This approach, although it has the advantage of simplicity, has the drawback of not reflecting the spatial-temporal differences of the energy mix used for energy production. In a scenario where the energy system is constantly changing and becoming more efficient, the use of static rather than dynamic factors can lead to an overestimation of the use of energy resources.

At European level, both the EED and the EPBD recommend the use of a total electrical PEF equal to 2.5 (in the absence of other adequately declared and justified factors) to express the consumption or savings in primary energy (Ferrari & Beccali, 2017). This assumption implies that a unit of electricity requires an input of 2.5 units of primary energy, with an average efficiency (including transmission, generation and distribution) of 40% (1 / 2.5 = 0.4). The assumption of these values was immediately questioned (European Heat Pump Association, 2017), pointing out the inadequacy and poor reliability: an electricity PEF equal to 2.5 does not correctly reflect the increasingly diversified electricity production made up of a constantly increasing renewable percentage (International Energy Agency, 2020). Furthermore, this factor disadvantages the diffusion of electric technologies in favor of traditional fossil fuels (Meggers et al., 2016). For example, the field of electric heating can become competitive only if favored by a lower PEF, allowing a fair comparison with fossil fuels conversion factors. Similar considerations can also be applied to district heating, as demonstrated in (Latõšov et al., 2017) and (Buonomano et al., 2012).

European Commission has also decided to commission a study in order to study the reliability of the current PEFs and study new methods of evaluation (Esser & Sensfuss, 2016), requesting the European Committee for Standardization (CEN) to provide a rigorous calculation standard for the PEF. The outcome was the drafting of EN 17423:2020 standard titled "Energy performance of buildings - Determination and reporting of Primary Energy Factors (PEF) and CO_2 emission coefficient - General Principles" (CEN – European Committee for Standardization, 2020) to support EN ISO 52000-1:2017 in order to complete the Energy Performance of Buildings (EPB) calculation and harmonize the methodology at European level (CEN – European Committee for Standardization, 2017b) that was recently adopted by National standardization bodies of EU countries.

1.1. Aim of the Work

From the analysis of the current literature (section 2), a widespread difficulty has emerged in uniquely calculating and comparing the energy performance of buildings in Europe. In the building energy performance sector, a correct classification and adequate comparison, remains a crucial and unsolved point. A rigorous and univocal technique for the calculation of primary energy conversion factors has not been used up to now (Hamels et al., 2021).

Most of the recently published studies have proposed calculation methods (Gustafsson et al., 2016), but not a unique calculation tool that can determine PEFs. The work contained in this paper fills this gap by applying the calculation methodology recently published in the EN 17423:2020 European standard and presented in section 3. The calculation methodology was applied to an evaluation procedure able to examine the data of a national energy balance as input and provide the PEFs of the electricity energy carrier as an output. Concerning input data, this work uses Eurostat energy balances, published annually for each country belonging to the Euro-zone. The aim of this work is to study the application of the recent EN 17423:2020 standard for the standardized calculation of the PEF of some European countries and apply its use for the energy assessment of buildings. The results obtained in this paper therefore represent a first step towards the unification and comparison of the energy performance of European buildings.

After a preliminary analysis, it was considered appropriate to focus the results of this work mainly on the primary energy factor of the electricity vector. This choice was supported by the greater variability in time and space of the energy flows relating to electricity, thus generating more interesting results and worthy of insights on the application to the performance of buildings (Hamels et al., 2021).

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2. Review of recent methodologies for the primary energy factors evaluation

In the literature there are numerous studies focused on the calculation of Primary Energy Factors (PEFs). In this paragraph some remarkable studies have been considered to understand the different strategies adopted in the calculation of PEFs. **Table 1** summarizes the main hypotheses and major results obtained by these studies. Early evidence of the problems in adopting regulatory PEFs for building energy performance assessments was demonstrated by Noris et al. (Noris et al., 2014) . The authors showed that the politically influenced primary energy or CO_2 conversion factors used to calculate annual primary energy or CO_2 emission have a strong impact on determining whether or not a building can be considered nZEB.

As early as 2014 Wilby et al. (Wilby et al., 2014) have tried to respond to the need to find an empirical tool for PEF evaluations. The authors developed an analysis tool, called the *Energy Network*, which numerically models and represents a country's energy system. Through the statistics of the International Energy Agency (IEA), the authors calculated the PEF of electricity and thermal energy on an annual basis, demonstrating that the factors values change depending on the year considered and the energy mix of the country. The study was conducted for many EU countries and for the OECD macro-area, evaluating years 2007-2009.

At the same time, Dixit et al. (Dixit et al., 2014) replicated the study for the US by comparing three different calculation methods. For all three methods, the calculated electricity PEF exceeded the value 4. The high value was justified by analyzing the electricity mix in the USA in 2002 (reference year for the study), which was entrusted for 50% to combustion of coal, 20% of nuclear, 10% of renewables and the remaining contribution to natural gas. Half of the total electricity supplied entrusted to the combustion of coal justifies the highest PEF found by the authors and equal to 4.64. However, Dixit showed that a variation in the calculation method can significantly change the result.

In the following years, two studies were commissioned at European level: the first carried out by the European Heat Pump Association (EHPA) (European Heat Pump Association, 2010), which supported a short study on the evolution of PEF values for EU-27+UK member countries in the years 2010-2013. GEMIS software was used to determine the PEFs for multiple energy carriers. This software calculates all primary energy inputs of fuels taking into account all phases of the life cycle. For the first time, the article reports the evolution of the total factors divided into a renewable and non-renewable share. The EHPA concludes by predicting that the trend in electricity PEF will decrease due to the increase in the renewable contribution.

The second study at European level was entrusted by the European Commission to the Fraunhofer institute and drawn up by Esser and Sensfuss (Esser & Sensfuss, 2016). In this study, four methods are proposed for calculating the PEF of electricity. Each method differs from the other according to i) the calculation of primary energy for renewables, ii) the method of allocating the energy input to CHP plants and finally, iii) adding an LCA to conventional fuels. The methods applied in this study can be summarized as follows:

- Method 1: Eurostat methodology

  - System boundaries: Total energy conversion only, including transport losses
  - Accounting method for power generation using non-combustible RES: Direct equivalent
  - Accounting method for CHP: IEA method
- Method 2: Life Cycle Approach
  - System boundaries: Entire supply chain
  - Accounting method for power generation using non-combustible RES: Zero equivalent
  - Accounting method for CHP: Finish method
- Method 3: Modified Eurostat methodology
  - System boundaries: Total energy conversion only, including transport losses
  - Accounting method for power generation using non-combustible RES: Direct equivalent
  - Accounting method for CHP: Finish method
- Method 4: Upper-end method
  - System boundaries: Entire supply chain
  - Accounting method for power generation using non-combustible RES: Direct equivalent
  - Accounting method for CHP: Finish method

For all four methods, the PEF calculated for the years 2000-2030 shows a continuous decreasing trend due to the increase in renewable technologies. The report explains the different choices of allocation methods for renewables and nuclear power and for the first time the methods are presented in a rigorous manner. The results of the Fraunhofer report were preparatory for CEN in the subsequent drafting phase of the EN 17423:2020 standard. As reported by Esser and Sensfuss, any choice made in determining a PEF must be declared in the annex to the legislation (there is no wrong method compared to another, as long as the choice made is specified).

After the publication of the European report, Rasheed et al. (Rasheed et al., 2019) replicated the calculations for South Korea, drawing similar conclusions. The authors used the four methods of the Fraunhofer report to show the variability between the different conventions, demonstrating that the factor has a decreasing trend over time, whichever method is chosen. For this reason, an analysis of the electrical PEF at least every 2 years was recommended.

More recently, two studies focused on Italy have been carried out. In the first, Noussan et al. (Noussan et al., 2018) investigated the trend of the electricity PEF from 2015 to 2016, adopting the "physical content method" and following IEA suggestion. In the second, Marrasso et al. (Marrasso et al., 2019) studied the efficiency of electricity generation from 2012 to 2017 (reciprocal value of the PEF). Both studies also calculate the CO_2 emission factor taking into account the percentage of electricity from renewable sources. The novelty reported by these two studies is the frequency with which performance indicators are calculated. In fact, both authors study the variability of conversion factors over the years, months and hours of the day. The accuracy of the results greatly depends on the quality of the data required, and the reliability of the indicators requires more and more detailed data. Both studies come to the conclusion that PEFs depend heavily on the generation mix and that they can have a very high seasonal variability.

The studies so far exposed are limited to the calculation of the PEFs and do not study the consequent possible applications. Two recent works have studied PEFs evaluation and their effects on the energy assessments of buildings primary energy consumptions.

In 2016 Gustanfsson (Swing Gustafsson et al., 2016) calculated the primary energy need for different Heating, Ventilating and Air Conditioning (HVAC) configurations serving a building for three specific countries (Finland, Denmark and Norway) and for the European average. In addition to electricity, other energy carriers such as biomass and solid waste were considered in order to analyze a building with three different HVAC systems. For the same final energy need, sixteen different configurations led to sixteen very different results in terms of primary energy.

Subsequently, in 2020, Troup et al. (Troup et al., 2020) studied the space-time impacts of the factors on the results obtained with Energy Plus simulation tool. The electrical PEF used in the software for the USA is 3.167 and does not take into account the regional differences that exist in the USA. Troup et al. first calculated PEFs at the regional level adopting two different conventions which are distinguished by the method of allocation of renewable technologies. Afterwards, the authors compared the primary energy need of an office in Atlanta deriving from the default values of the software with those deriving from their calculation method (the building had a need for electricity and natural gas). The method of allocating renewables heavily changes the outcome of the results, but in both cases it was found that the default value significantly overestimates the real values (in some regions the real values are reduced by 50%). Consequently, primary energy of the case study is reduced by 19% in 2020 compared to the value calculated with EnergyPlus. This latter study adopts a similar methodological approach (PEF calculation and application on a case study) which will be presented in this paper.

Table 1 summarizes all the studies taken into consideration, specifying the temporal development of the studies, the reference geographical area, the timestep adopted (annual-y, monthly-m, hourly-h) and the calculated electrical PEF. In the case of a calculation that varies over time, two values of the electrical PEF have been reported, representing the minimum and maximum variation range.

This section has analyzed the various attempts of the scientific community to propose a rigorous and reliable calculation method for the evaluation of PEFs for electricity. The relevant result of the literature analysis lies in the strong variation of the PEF calculated in different studies. The presence of discordant PEF values referring to the same geographical areas is a clear example of how a standardized calculation was not applied in the past. The values analyzed by the literature analysis use different calculation methods and approaches that do not allow an adequate comparison for present and future energy policies (Hamels, 2021). The analysis of the literature has therefore shown the need for a standardization in the calculation of PEFs for the evaluation of the performance of buildings This work applies the new standard EN 17423:2020, following a rigorous and repeatable method, marking a step forward compared to the commented works.

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Table 1 - Summary of boundary conditions and electricity PEFs from the literature analysis.

Authors		Year of publication	Year of analysis	Geographical area	Time-step[a]	PEF [kWh/kWh][b]	Reference
Dixit et al.		2014	2002	USA	y	4.12	(Dixit et al., 2014)
		2014	2007-2009	OECD	y	4.22	
		2014	2010-2013	EU-27+UK	y	4.64	
Wilby et al.		2014	2007-2009	OECD	y	2.79[c]	(Wilby et al., 2014)
IINAS		2014	2010-2013	EU-27+UK	y	2.49-2.47	(European Heat Pump Association, 2010)
Fraunhofer (Esser)	Method 1	2016	2000-2030	EU-27+UK+Norway	y	2.41-1.74	(Esser & Sensfuss, 2016)
	Method 2				y	2.41-1.35	
	Method 3				y	2.52-1.87	
	Method 4				y	2.65-1.93	
Gustafsson et al.		2016	2011-2013	Sweden	y	2.36-1.63	(Gustafsson et al., 2016)
Noussan et al.		2018	2015-2016	Italy	y	2.00-1.92[d]	(Noussan et al., 2018)
					m	2.00-1.90[d]	
					h	2.10-1.80[d]	
Marrasso et al.		2019	2012-2017	Italy	y	2.27-1.40[e]	(Marrasso et al., 2019)
					m	2.50-0.94[e]	
					h	2.50-0.59[f]	
Rasheed et al.	Method 1	2019	1980-2015	Republic of Korea (Sud Korea)	y	3.07-2.21	(Rasheed et al., 2019)
	Method 2				y	2.10-1.93	
	Method 3				y	3.08-2.50	
	Method 4				y	3.26-2.64	
Troup et al.		2020	2020-2050	USA	y	2.56-2.00	(Troup et al., 2020)

LEGEND:

[a] y: yearly; m: monthly; h: hourly

[b] Minimum-Maximum where double values are presented

[c] OECD considered, but there are also values for many European countries, for the USA and for Japan

[d] Average values between 2012 and 2017

[e] Average values between 2016 and 2017

[f] Value of 2016

3. Methodology

The methodology presented in this section aims to assess the primary energy needs for 37 case study buildings spread over 11 European countries. To achieve this goal, however, it was necessary to develop a detailed framework summarized in **Figure 1**, which can be divided into three main steps:

- Step 0: collection and organization of input data and necessary sources. To perform a uniform calculation method for all countries, three European data sources were used: (i) the EN 17423:2020 standard for the calculation procedure of primary energy factors, (ii) the yearly energy balances of European countries provided by Eurostat statistics, and (iii) the TABULA typical buildings used as reference case study buildings for energy performance evaluation (Loga et al., 2016).
- Step 1: calculation of primary energy factors. This step, presented in section 3.1, shows the procedure adopted for calculating the primary energy factors for electricity during the years 2000-2019 for 11 European countries. The values of the factors were calculated following the EN 17423:2020 technical standard, using the data published annually by Eurostat energy statistics. This step aims at calculating the non-renewable ($f_{P,nren,del,el}$) and renewable ($f_{P,ren,del,el}$) primary energy factors for electricity (**output 1.1** of the framework). In addition to the PEF calculated according to EN 17423:2020 it was considered appropriate to collect other available PEF values for comparison purposes. Therefore, although not the result of a calculation method, Step 1 also collects the European average values established in the standard EN ISO 52000-1:2017 (**output 1.2** of the framework) and the values established by national regulation and valid exclusively within individual states (**output 1.3** of the framework). Step 1 ends with the collection of 3 sets of PEFs for electricity. The calculated factors have been used as input data of Step 2.
- Step 2: application of the calculated PEF for the assessment of building primary energy needs. This step, described in section 3.2, presents the application of primary energy factors for electricity on 37 case studies selected from TABULA typical buildings. All reference case studies are fully electric nZEBs and belong to 11 different European countries. The annual primary energy needs (PE) for space heating were evaluated and compared. For each case study building considered, primary energy ([kWh/m^2]) was evaluated using the primary energy factors assessed in the Step 1 following three different methods:
    1. PE evaluation in the period 2000-2019 deriving from the PEF calculated in section 3.1, according to the EN 17423:2020 standard (**output 2.1**).
    2. PE evaluation using constant primary energy factors from EN ISO 52000-1:2017 (**output 2.2**). This output is independent from the year or the country of analysis.
    3. PE evaluation according to the national regulation in force on the European countries analyzed (**output 2.3**).

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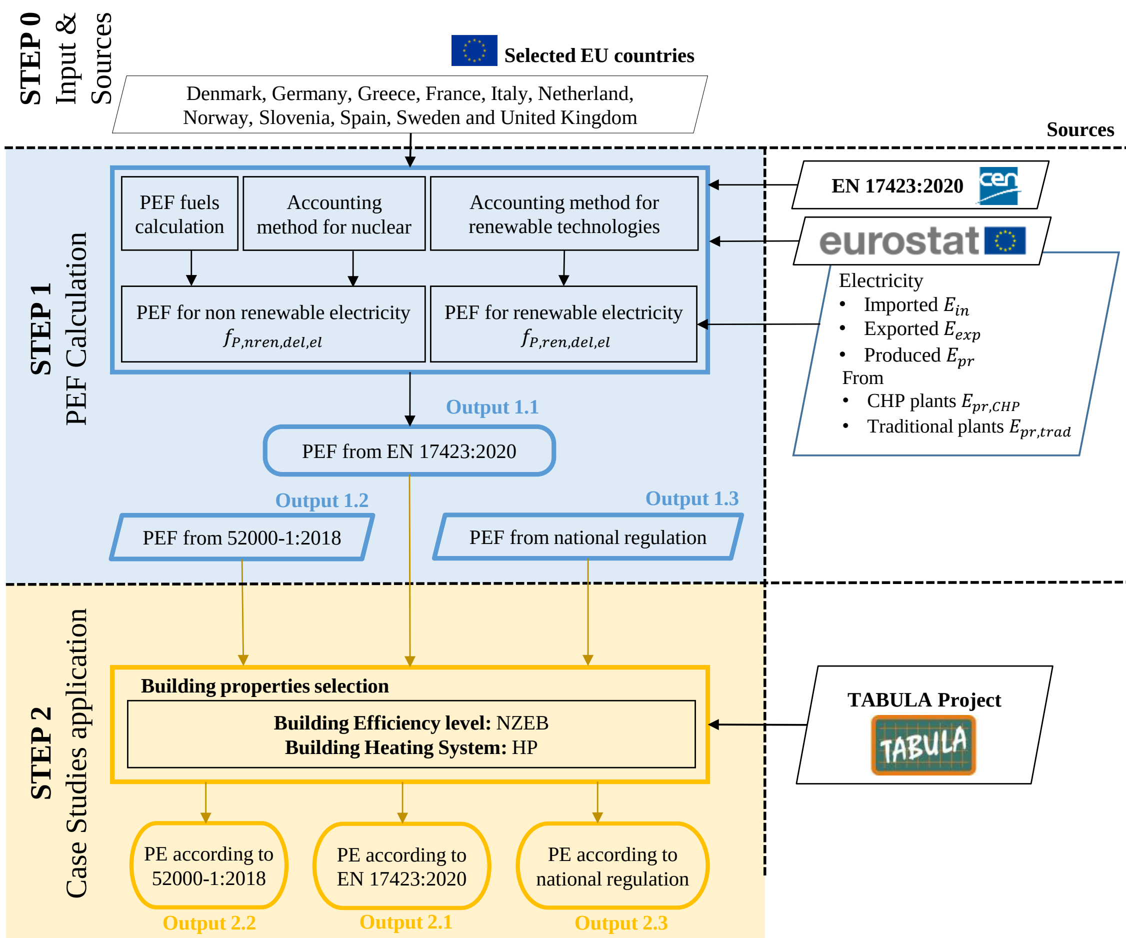

Figure 1 - Methodological framework adopted in the work.

3.1. Electric primary energy factor ($f_{P,tot,del,el}$) calculation for 11 European countries (Step 1)

Eurostat organization provides energy balances for all EU countries on the basis of standardized methodologies (Eurostat, 2020). The energy balance database is available online and updated annually. For each fuel product and energy generation technology, the energy flows from production to final use are quantified. The flows include all types of energy produced and consumed, entering and leaving national borders.

Eurostat provides comparable data for several European countries and for a time sequence of several years. In this work, the primary energy factors of electricity were calculated annually, from 2010 to 2019 (last year available on the Eurostat statistics to date) for eleven selected countries: Denmark, France, Germany, Greece, Italy, UK, Norway, The Netherlands, Slovenia, Spain and Sweden. For the analysis of the data, the procedure uses Eurostat energy balance (of any year and country) as input source and produces as output the primary energy factor of electricity divided into its two forms, renewable and non-renewable, $f_{P,ren,del,el}$ and $f_{P,nren,del,el}$, respectively. The approach of calculating the non-renewable and renewable shares of the primary energy factor is of fundamental importance to correctly assess the actual energy use within a building (Zirngibl, 2020). Furthermore, the correct evaluation of the two shares of PEF allows an unbiased evaluation of the energy resources used, without being influenced from political or industrial choices. As reported in Equation (2), the sum of renewable and non-renewable factor represents the total electricity factor:

$$f_{P,TOT,del,el} = f_{P,nren,del,el} + f_{P,ren,del,el} \left[\frac{kWh}{kWh}\right] \quad (2)$$

where del indicates delivered (energy).

The EN 17423:2020 standard proposes a univocal and standardized calculation method that allows the procedure to be replicated: it is necessary to declare the choices made in order to make the calculation of the indicators transparent and rigorous. It is therefore essential to report the space and time boundaries adopted in the calculation phase. Since the Eurostat statistics has an annual frequency and respects national boundaries, all the following calculations inherit these boundary conditions (European Commission, 2019). The other assumptions adopted for this study are presented in the following paragraphs.

The EN 17423:2020 standard requires the calculation to be made by separating the values of the factor relating to the non-renewable share $f_{P,nren,del,el}$ from that relating to the renewable share $f_{P,ren,del,el}$. Non-renewable factor derives from the contribution on the national electricity grid of traditional thermal power or cogeneration plants that exploit the combustion of non-renewable fossil sources. The electricity produced by nuclear power plants also contributes to the calculation of the non-renewable factor; in this work, the same Eurostat convention was chosen, i.e., an average conversion efficiency of 33% is assumed. The renewable factor, on the other hand, is derived from the contribution of renewable technologies to the national grid (wind, solar, hydro, etc.). The calculation procedure considers energy exchanges within the national borders. **Figure 2** graphically represents the national boundaries under analysis and the incoming and outgoing electricity flows to be considered for the evaluation of the primary energy factor of the delivered electricity, recalling the methodological approach suggested in the EN 17423:2020 standard.

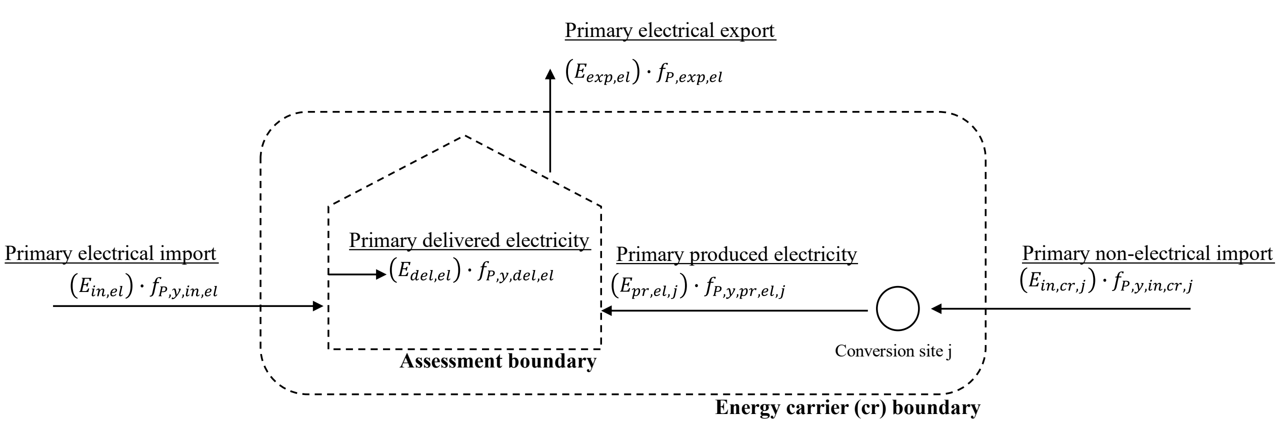

Figure 2 - Global evaluation of the energy flows for the electricity primary energy factor.

Figure 2 schematizes the calculation methodology adopted to evaluate the PEF for electricity according to the EN 17423:2020 standard. The same energy flows are recalled by the Equation (3), as also reported in EN

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17423:2020 standard, which mathematically describes the same concept and constitutes the starting point for the evaluation of the PEF for electricity.

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

where:

- E indicates an energy flow of the generic energy carrier.
- f_P is the primary energy factor relating to the energy flow considered.
- y indicates the fraction considered, whether it is non-renewable $nren$, renewable ren or total tot;
- j indicates the j-th energy carrier flow considered for production (when multiples are involved).

The description of the quantities involved in **Figure 2** and Equation (3) were summarized in **Table 2.** For each quantity, the source or evaluation method is reported. When the Eurostat balance sheet is mentioned, it means that the quantities have been obtained using that resource. In addition, it is appropriate to specify that for each energy flows E, the Eurostat balance sheet allows to distinguish renewable and non-renewable share.

Table 2 – Main sources and methodological assumption for the evaluation of primary energy factor for electricity.

Nomenclature	Description	Source or methodological evaluation
$E_{in,el}$	electricity imported within the assessment boundary	Eurostat balance sheet: "Supply block - Imports", electricity vector
$E_{exp,el}$	electricity exported out of the assessment boundary	Eurostat balance sheet: "Supply block - Export", electricity vector
$E_{pr,el,j}$	electricity produced within the assessment boundary under analysis relating to the j-th carrier (fuel)	Eurostat balance sheet: "Gross electricity and heat production block", electricity vector, carrier j-th
$E_{del,el}$	total electricity delivered for final use	$E_{del,el} = \sum_j E_{pr,el,j} + E_{in,el} - E_{exp,el}$
$E_{in,cr,j}$	energy flow related to the j-th carrier (fuel) entering the energy conversion sites	Eurostat balance sheet: "Transformation input block", carrier j-th
$f_{P,y,in,el}$	Primary energy factor for imported electrical energy	Assumed as European average as indicated in Annex B of EN ISO 52000-1:2017. $f_{P,nren,in,el}$ = 2.3 and $f_{P,ren,in,el}$ = 0.2
$f_{P,y,exp,el}$	Primary energy factor for exported electrical energy	Assumed equal to $f_{P,y,pr,el}$ as it is considered that the exported energy is entirely produced within the national borders
$f_{P,y,pr,el,j}$	Primary energy factor for produced electrical energy using j-th carrier (fuel)	Derived following EN 17423:2020 methodology. See section 3.1.1
$f_{P,y,del,el}$	Primary energy factor for delivered electrical energy	Equation (3) from EN 17423:2020 methodology
$f_{P,y,in,cr,j}$	Primary energy factor for the j-th carrier (fuel) entering the energy conversion sites	Eurostat balance sheet: "Supply block – Available for final consumption", "Supply block – Energy sector and distribution losses" to evaluate:

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		$f_{P,in,cr} = \frac{Avaibale\ for\ final\ consumption + losses}{Available\ energy\ for\ final\ use}$

The solution of Equation (3) leads to the evaluation of the primary energy factor for electricity and therefore constitutes the **output 1.1** of this work. Most of the quantities necessary for the solution of Equation (3) were obtained from the resources mentioned in **Table 2**. However, the evaluation of the primary energy factor for the electricity produced within the national borders needs a detailed analysis, always applying the methodology proposed in the standard EN 17423:2020. The calculation of this quantity has been addressed in section 3.1.1.

3.1.1. Primary energy factor for produced electricity using carrier (fuel) j ($f_{P,y,pr,el,j}$)

After declaring the assumptions made on the factors relating to the shares of imported and exported energy, the main primary energy conversion factors of production within the national borders, $f_{P,nren,pr,el}$ and $f_{P,ren,pr,el}$, can be evaluated.

Primary energy factor for electricity produced by renewables, $f_{P,ren,pr,el}$, can be evaluated using one of the conventional methods so far proposed in the literature (Stoffregen & Schuller, 2014). In this work, the "Method of physical content" was adopted, also chosen by Eurostat as reference method. The general principle of this method is that the primary energy form is taken as the first flow in the production process that has a practical energy use. Electricity is considered as the primary energy form for solar photovoltaic, wind, hydro, tide, wave, ocean, leading to a 100% efficiency ($f_{P,ren,pr,el} = 1$). For other renewable energy resources such as solar thermal and geothermal, heat is considered as the primary source of energy produced. Therefore, if these resources were used for electricity production, efficiencies equal to 30% and 10% are considered for solar thermal and geothermal, respectively ($f_{P,ren,pr,el} = 10\ or\ 3$). The methodological choices made in this study share the conventions proposed by Eurostat when considering primary energy flows from renewables and have been summarized in **Table 3**.

Table 3 - Eurostat's methodology according to "Physical energy content" for renewable electricity production efficiencies.

	Renewable sources			
	Geothermal	Concentrating solar	Solar thermal	Hydro, wind, PV
Efficiencies or conventions	10 %	33 %	30 %	100 %
$f_{P,ren,pr,el}$	10	3.3	3	1

On the other hand, the non-renewable factor must consider both the electricity production from traditional ($trad$) plants and that from cogeneration (CHP) plants; both contributions must be multiplied by the related primary energy factor:

- $f_{P,nren,pr,el,trad}$ indicates the factor related to production from traditional power plants. The calculation is based on the definition of primary energy factor (Equation (1))

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- $f_{P,nren,pr,el,CHP}$ indicates the factor related to production from cogeneration plants (CHP). This factor takes into account that electricity is not the only output product of the power plant.

In fact, the EN 17423:2020 standard requires taking into account the different outputs of a cogeneration plant and proposes a specific assessment that is summarized in **Figure 3**.

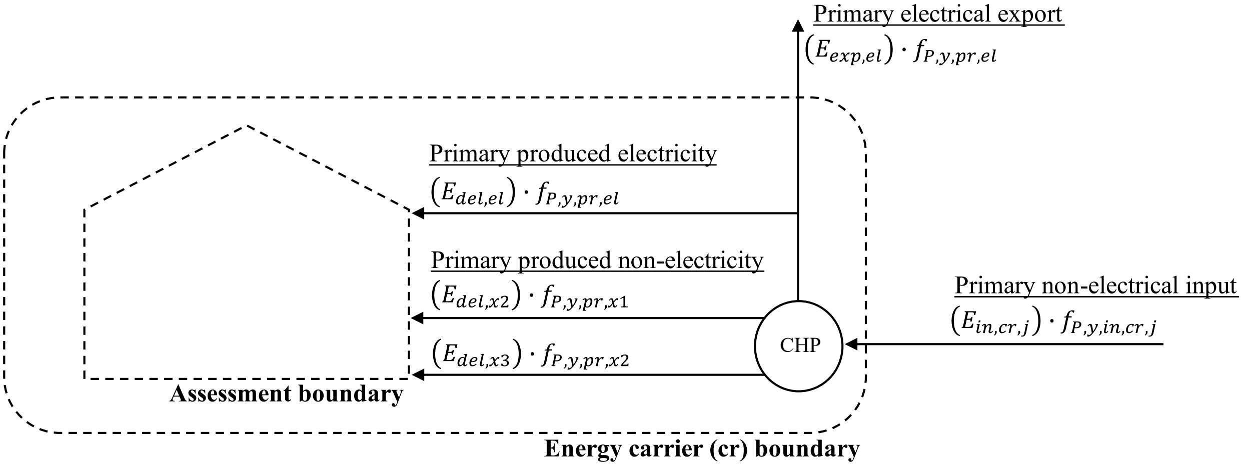

Figure 3 - Schematics of a multi-output CHP power plant with exported electrical energy.

Again, considering only the electrical output, **Figure 3** can be mathematically interpreted as suggested by the methodology of the EN 17423:2020 standard through Equation (4). However, in the case of multi-energy systems such as CHP it is necessary to consider that not all the primary energy input will be used to produce electricity. For this reason, the energy input must be weighted by an electricity allocation factor a_{el}.

$$f_{P,nren,el,CHP} = \frac{\sum_j (E_{in,cr,j}) \cdot f_{P,nren,in,cr,j}}{E_{del,el}} \cdot a_{el} \quad (4)$$

where:

- $f_{P,nren,in,cr,j}$ is the primary energy factor of the single j-th carrier (fuel) used in the CHP plant (see Table 2 for evaluation).
- x_1 and x_2 are additional output energy vectors from the CHP plant (for example: thermal energy, cooling energy in case of trigeneration plants (Chicco & Mancarella, 2007)).
- a_{el} is the electricity allocation factor.

Different methods can be adopted for the evaluation of allocation factors (CEN – European Committee for Standardization, 2017a). This work adopts the "Alternative production method", which requires thermal and electrical conversion efficiencies as inputs, as reported in Equation (5).

$$a_{el} = \frac{\frac{E_{el}}{\eta_{el,ref}}}{\frac{E_{el}}{\eta_{el,ref}} + \frac{Q_{cm}}{\eta_{th,ref}}} \quad (5)$$

where

- $\eta_{el,ref}$ is the reference conversion efficiency for electricity production.

- $\eta_{th,ref}$ is the reference conversion efficiency for heat production.

The efficiencies $\eta_{el,ref}$ and $\eta_{th,\mathrm{ref}}$ were set as fixed values 0.4 and 0.9 respectively, according to EN 15316-4-5:2017.

The calculation method proposed by EN 17423:2020 standard, presented in Equation (4), favors cogeneration plants, because it allows to only consider the primary energy really needed for the production of a single output. The factors obtained from the two categories of power plants, $f_{P,nren,pr,el,trad}$ and $f_{P,nren,del,el,CHP}$, enable the evaluation of $f_{P,nren,pr,el}$.

After calculating the primary energy factors related to production, it is possible to solve Equation (3), considering the exchanges with the boundaries and determining the final primary energy factors, $f_{P,nren,del,el}$ and $f_{P,ren,del,el}$. The application of this methodology allows to obtain the trends of the electricity factors from 2010 to 2019 for the selected European countries. Results are reported in section 5.1.

3.1.2. Calculation tool validation

This section is dedicated to the validation of the calculation tool that implements the EN 17423:2020 standard for the evaluation of primary energy factors for electricity, as described in previous section.

To validate the calculation tool, the report of (Esser & Sensfuss, 2016) was used as a reference, using the same boundary parameters in terms of geographical area of analysis and years of analysis. In particular, the following input data were used:

- Geographical resolution: EU 28 (European Union plus Norway).
- Years of analysis: 2000, 2005, 2010, 2015.
- Energy balance: coming from "advanced calculations based on statistics and studies" for the reference values. In the case of the calculation tool, Eurostat statistics is declared as the data source.

Regarding the reference output, the value of the total primary energy factor for electricity ($f_{P,TOT,el}$) was considered.

The results obtained by comparing the reference and calculated values are collected in **Figure 4**. The percentage deviations of the results never exceed the maximum absolute value of 1.26%, while the mean bias error (MBE) between the reference and calculated values is 0.018.

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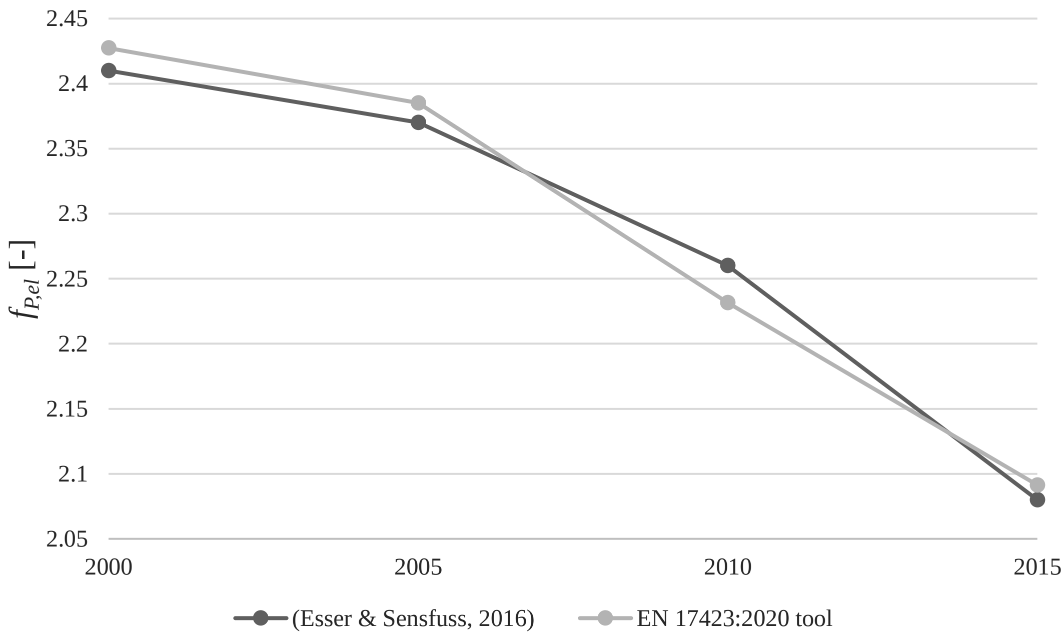

Year	Reference	Calculation	Statistics	
	(Esser & Sensfuss, 2016)	EN 17423:2020 tool	Deviation [%]	MBE [-]
2000	2.41	2.43	0.72%	0.018
2005	2.37	2.39	0.64%	
2010	2.26	2.23	-1.26%	
2015	2.08	2.09	0.55%	

Figure 4 – Primary energy factor for electricity evaluated for EU28. Comparison between the application of calculation tool from EN 17423:2020 and Esser & Senfuss report.

The comparison reported in this section allowed to consider the calculation method implemented as valid and reliable. The benchmark considered for the analysis just shown was considered the most correct and adequate for the purposes of this work.

3.2 Application to case studies (Step 2)

According to the latest EPBD recast, to quantify the primary energy needs it is first necessary to assess the final energy needs of the building. The final energy need of a building includes winter and summer air conditioning, lighting, ventilation, domestic hot water and people transport services. After quantifying the final energy and its energy carrier (electricity, natural gas, district heating, etc.), it is possible to calculate the primary energy by multiplying the final energy of each energy carrier by the corresponding primary energy factor.

To compare the energy performance of some European buildings, case studies from TABULA typical buildings have been selected (Loga & Stein, 2016). TABULA was developed from the collaboration of 21 countries with the aim of creating a harmonized collection of the energy performance of different European building. TABULA collects the energy simulations of buildings belonging to four categories, with variable construction years from 1900 up to 2010, and with three levels of renovation: state of the art (low energy performance), standard renovation and advanced renovation (high energy performance) (Visscher et al., 2016). The four categories of buildings studied are: Single Family House (SFH), a building with a single living unit; Multi Family House (MFH), a building characterized by a limited number of apartments; Terraced House (TH), a multi-family building bordering with other residential units; Apartment Block (AB), a multi-family building with sixteen or more apartments.

The results achieved with TABULA describe the energy consumption of the buildings for three services (heating, DHW and ventilation), both in terms of final energy and primary energy. For the calculation of primary energy, TABULA uses an electrical $f_{P,nren,el}$ equal to 2.3 and $f_{P,ren,el}$ equal to 0.2, as suggested by EN ISO 52000-1:2017.

Starting from the data of TABULA, for the purposes of this work the following methodological choices were made:

1. Newly constructed buildings considered "Ambitious standard / nZEB" have been selected to allow a study between buildings that require a comparable share of final energy (D'Agostino & Mazzarella, 2019).
2. Only buildings with Heat Pumps systems were considered. This choice made it possible to highlight the effects of the primary energy factors of the energy carrier "electricity". For each case study, heating and ventilation energy needs were considered. The nZEB configuration considers a sensible energy recovery through the installation of a heat exchanger on the ventilation system. Domestic hot water production has not been taken into consideration, due to its important variation depending on the state considered, even considering the same types of buildings. Furthermore, there is greater technological variability in satisfying DHW in different states, not always making electricity a widely used energy carrier.

For each of the 11 selected countries it has not always been possible to identify a case study for each building category (SFH, MFH, TH, AB) capable of respecting the two constrains set out above (nZEB + only electrical building). These two constraints led to the selection of 37 case studies. For each selected building, the corresponding primary energy was evaluated by applying the three alternative sets of primary energy factors represented by outputs 1.1, 1.2 and 1.3 of the work (see methodological framework in **Figure 1**). The first set includes the primary energy factors obtained following the rigorous calculation of EN 17423:2020 illustrated in section 3.1; the second set includes the values shown in Annex B of EN ISO 52000-1:2017. The last set includes the primary energy factors proposed by national laws (where available). The results relating to the PEFs for electricity (output 1.1, 1.2, 1.3 of the framework) and the results of primary energy need of the case study buildings (outputs 2.1, 2.2, 2.3 of the framework) are presented in section 5.

4. Case studies

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The 37 case studies selected for this work, coming from TABULA typical buildings, are reported in **Table 4**. The table summarizes the main characteristics of the selected case studies indicating the country of origin, the type of building, the conditioned area and the heat pump typology. Furthermore, the data used for the energy assessments are reported, which concern the values of energy need for heating and ventilation, the heat pump energy expenditure coefficient, the electricity need for auxiliaries and the finale electrical delivered energy. Specifically, **Table 4** collects the following numerical values:

1. Heating and ventilation thermal energy need of the building, with ventilation heat recovery ($q_{g,h,out}$, - *specific heat generator output*), using a fixed recovery efficiency of 0.80 for the ventilation system, as set by TABULA .
2. The constant energy expenditure coefficient $e_{g,h}$, adopted as a global efficiency indicator for the heating generators used within the TABULA project (Loga et al., 2012).
3. The electricity need for the operation of the auxiliaries of the heating service $q_{del,h,aux}$ and of the ventilation $q_{del,ve,aux}$.
4. The *Electrical delivered energy* $E_{el,del}$, i.e. the electricity consumed by HVAC system (Heat Pump in the selected cases) to meet space heating demand with heat recovery. Delivered energy also considers the electricity needed by auxiliary systems, and is evaluated by Equation (6):

$$\mathrm{E_{el,del}} = q_{g,h,out} \cdot e_{g,h} + q_{del,h,aux} + q_{del,ve,aux} \left[\frac{kWh}{m^2 \cdot a}\right] \quad (6)$$

For more details on the quantities involved, please refer to TABULA (Loga et al., 2016). In addition, the Table includes in the last column the unique reference code that refers to the TABULA building.

Table 4 - Case studies buildings.

Country (Code)	Building Type	Area [m^2]	$q_{g,h,out}$ $\left[\frac{kWh}{m^2 \cdot a}\right]$	Heat Pump Typology	$e_{g,h}$ [-]	$q_{del,h,aux}$ $\left[\frac{kWh}{m^2 \cdot a}\right]$	$q_{del,ve,aux}$ $\left[\frac{kWh}{m^2 \cdot a}\right]$	$E_{el,del}$ $\left[\frac{kWh}{m^2 \cdot a}\right]$	TABULA Code
Denmark (DK)	SFH	151	15.9	ground-water	0.25	3.2	3.0	10.2	DK.N.SFH.10
	TH	132	13.0	ground-water	0.25	3.2	3.0	9.5	DK.N.TH.10
	AB	6988	10.6	ground-water	0.25	3.2	4.6	10.5	DK.N.AB.10
France (FR)	SFH	103	22.6	air-water	0.40	0	3.1	12.1	FR.N.SFH.10
	TH	93	13.8	air-water	0.40	0	3.1	8.6	FR.N.TH.10
	MFH	851	14.0	air-water	0.40	0	3.1	8.7	FR.N.MFH.06
	AB	3348	9.8	air-water	0.40	0	3.0	6.9	FR.N.AB.06
Germany (DE)	SFH	187	21.0	ground-water	0.29	6.1	2.6	14.8	DE.N.SFH.11
	TH	196	15.5	ground-water	0.29	6.1	2.6	13.2	DE.N.TH.11
	MFH	1305	12.8	ground-water	0.29	1.8	2.6	8.1	DE.N.MFH.11
Greece (EL)	MFH	357	14.3	ground-water	0.14	5.5	0.0	9.0	GR.ZoneA.MFH.03
	SFH	217	18.5	ground-water	0.19	5.5	0.0	7.5	GR.ZoneA.SFH.03
Italy (IT)	SFH	174	15.3	ground-water	0.29	2.7	1.4	8.5	IT.MidClim.SFH.08
	TH	127	15.4	ground-water	0.29	2.7	1.4	8.6	IT.MidClim.TH.08

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	MFH	829	11.4	ground-water	0.29	1.6	1.4	6.3	IT.MidClim.MFH.08
	AB	2125	9.5	ground-water	0.29	1.6	1.4	5.8	IT.MidClim.AB.08
Netherlands (NL)	SFH	186	17.8	air-water	0.45	2.8	4.2	15.0	NL.N.SFH.05
	TH	137	13.3	air-water	0.45	2.8	4.2	13.0	NL.N.TH.05
	MFH	3032	11.9	air-water	0.45	2.8	4.2	12.4	NL.N.MFH.05
	AB	3235	12.8	air-water	0.45	2.8	4.2	12.8	NL.N.AB.05
Norway (NO)	SFH	184	28.9	air-water	0.40	3.8	3.0	17.9	NO.N.SFH.07
	TH	198	27.8	air-water	0.40	3.8	3.0	18.4	NO.N.TH.07
	AB	1065	35.4	ground-water	0.31	5.5	4.0	20.5	NO.N.AB.06
Slovenia (SI)	SFH	287	43.8	ground-water	0.29	2.7	2.0	17.4	SI.N.SFH.06
	TH	188	62.0	air-water	0.36	2.7	2.0	16.5	SI.N.TH.06.003
	MFH	1851	30.4	ground-water	0.29	2.7	2.0	13.5	SI.N.MFH.06.003
	AB	6066	32.5	ground-water	0.29	2.7	2.0	14.1	SI.N.AB.06
Spain (ES)	SFH	163	6.0	air-water	0.50	0	0.0	3.0	ES.ME.SFH.05
	TH	162	7.1	air-water	0.50	0	0.0	3.6	ES.ME.TH.05
	MFH	748	2.6	air-water	0.50	0	0.0	1.3	ES.ME.MFH.05
	AB	2323	3.5	air-water	0.50	0	0.0	1.8	ES.ME.AB.05
Sweden (SE)	SFH	106	60.7	ground-water	0.33	8.1	2.0	30.1	SE.N.SFH.05
	MFH	1207	20.5	air-water	0.33	12	2.0	20.8	SE.N.MFH.05
UK	SFH	149	18.5	air-air	0.40	1.3	2.0	10.7	GB.ENG.SFH.08
	TH	98	18.2	air-air	0.40	1.3	2.0	10.6	GB.ENG.TH.08
	MFH	994	8.2	air-air	0.40	1.3	2.0	6.6	GB.ENG.MFH.08
	AB	4357	47.1	air-air	0.40	1.3	0.0	20.1	GB.ENG.AB.04

The calculations were performed using the delivered energy values $E_{el,del}$ reported on the TABULA simulations as input for the primary energy analyzes of the buildings.

5. Results

5.1 Primary energy factors according to EN 17423:2020 (Output 1.1)

The calculation of primary energy factors following the guidelines of EN 17423:2020 led to the results shown in **Figure 5**, which reports the trend in the years 2000, 2010, 2015, 2019 of the total electrical primary energy factor divided into renewable $f_{P,ren,el}$, in green, and non-renewable $f_{P,nren,el}$, in red; the height of the columns indicates the $f_{P,TOT,el}$. The results in **Figure 5** correspond to Output 1.1 established in the framework (see **Figure 1**). Numerical values obtained for the development of **Figure 5** have been comprehensively reported in **Table A1**, in the Appendix, for the whole period 2000-2019.

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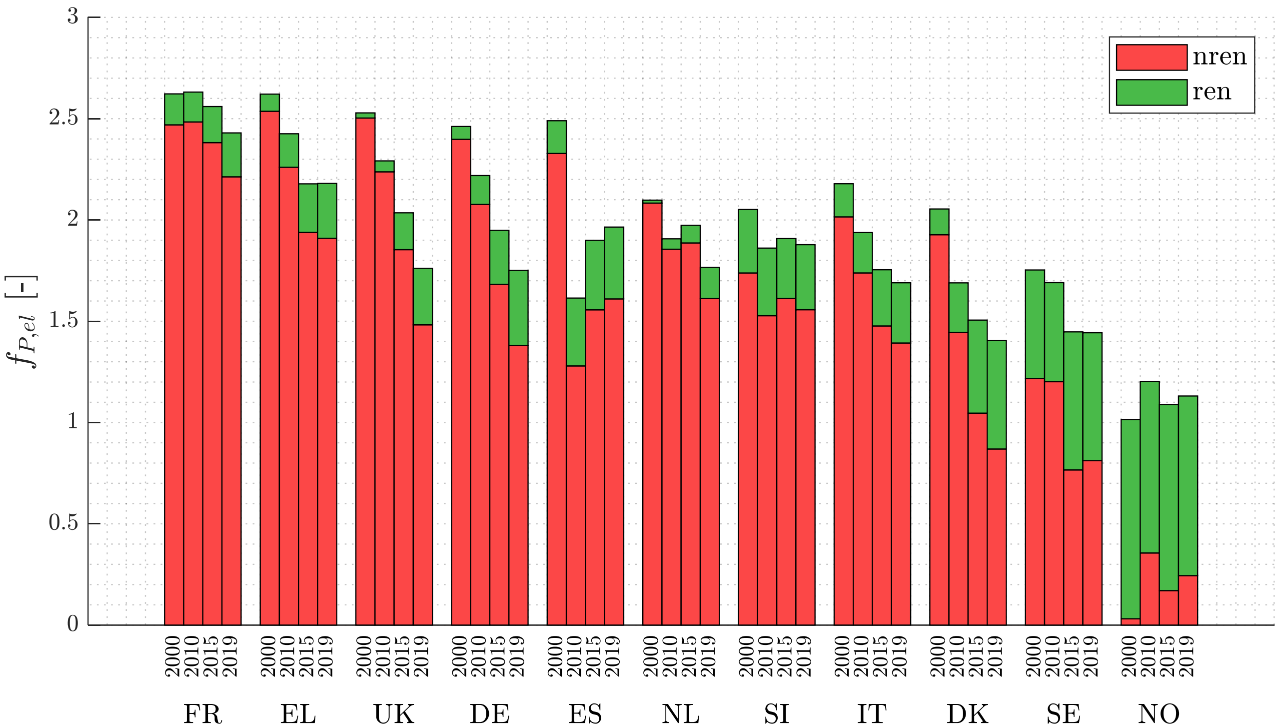

Figure 5 - Electrical primary energy factor evaluated according to EN 17423:2020 applied on national balances of the years 2000, 2010, 2015, 2019.

In the twenty years analyzed, all eleven European countries reduce the value of $f_{P,TOT,el}$ by an average value of 17.2%. This trend can be justified by a greater efficiency of generation systems and the simultaneous diffusion of renewable technologies. Considering only the non-renewable primary energy factor, the average reduction in the states considered is equal to 30.1%, indicating an evolution in the efficiency of electricity generation and distribution systems. For countries such as Denmark, Germany, Italy, Spain and the UK, the decreasing trend is evident. European countries such as Denmark and Germany demonstrate that energy transition policies adopted in the last twenty years are noticeable in terms of the growth of the renewable primary energy factor, which has practically tripled.

A clear example is that of Germany, whose $f_{P,ren,el}$ increased from 0.06 in 2000 to 0.37 in 2019; similarly, in Denmark the primary renewable energy factor increased from 0.13 in 2000 to 0.53 in 2019, representing the best growth among European countries, certainly justified by a strong energy transition policy based on wind renewable sources.

On the other hand, considering Italy, there is a relevant decrease in the non-renewable primary energy factor, reduced from 2.02 to 1.39 during the years taken into consideration, demonstrating targeted investments in fossil resources and their generation energy efficiency and distribution. On the contrary, a different result is obtained for countries such as Spain and the UK, which despite being good producers of renewable energy, still have high values of the non-renewable primary energy factors $f_{P,nren,el}$. This phenomenon is certainly affected by the production of electricity from nuclear power plants, widely used in both states, and considered by the standard to be entirely non-renewable sources.

Norway is the country among those studied with the most important impact from renewable production, making the most of its renewable resources (mainly from hydro) since 2000. The primary energy factor for electricity in Norway has a trend between 1.0 and 1.2 during the years analyzed. Furthermore, the renewable contribution $f_{P,ren,el}$ presents rather constant values, confirming that Norwegian electricity production, largely coming from hydroelectric power plants, has already been developed since 2000 (International Energy Agency, 2022). The increase in national electricity demand, however, made it essential to install new fossil fuel plants after 2000, thus influencing the non-renewable share of electricity production. After Norway and Denmark, Sweden is the country with the largest share of renewable production even though the energy mix has remained unchanged over the years. Sweden has reached one of the lowest $f_{P,TOT,el}$, that was 1.44 in 2019, corresponding to a generation efficiency of 69%. Swedish non-renewable share is instead attributable to the production of electricity from natural gas.

Interested results can also be highlighted for Spain, whose trend of $f_{P,TOT,el}$ undergoes a significant drop in 2010. This result can in fact be linked to the economic situation that Spain experienced during the period 2008-2012, facing a significant economic recession. In those years the national energy demand suffered the lowest values of the last twenty years and the consumption of coal reached its minimum (International Energy Agency, 2021). This situation, supported by the investments made for the diffusion of renewable energy resources, has made it possible to satisfy a large part of the Spanish energy demand by avoiding the consumption of fossil fuels in plants with lower efficiencies, therefore resulting in a decrease in its primary energy factor for electricity.

For France, the Netherlands, Greece and Slovenia, the factor has a moderate reduction over the years: although France has supported substantial investment policies on renewable sources, the contribution from nuclear power plants prevails, resulting in a $f_{P,TOT,el}$ never below 2.4. Over the years the Netherlands and Greece have reduced the contribution of solid fuels in favor of natural gas, slightly increasing the renewable contribution. However, the prevailing component of $f_{P,TOT,el}$ remains the non-renewable share. Finally, Slovenia in the last twenty years always had a stable electricity production, without particular changes to energy policies; as a result, its $f_{P,TOT,el}$ has not undergone major variations, as well as its renewable and non-renewable shares.

This first result demonstrates the continuous evolution of the electrical primary energy factor, which is an important indicator for tracing the energy policies and investments adopted by the countries. The consequence of this result is the need for a legislation that updates primary energy factors periodically.

These considerations, applied to the assessment of buildings energy performance, can lead to even more detailed results. Taking Italy as an example, **Figure 6** reports the historical evolution of the electrical primary energy factors adopted by the Italian legislation in the years 2000-2019, compared with the trend evaluated according to EN 17423:2020. The breakdown of the renewable and non-renewable shares, represented in the bar graph, was assessed using the methodology illustrated in the previous section. With regard to the legislative aspect, Italy set up, starting from 1993, a conversion factor of electricity into primary energy $f_{P,el}$ equal to 2.77 (Italian Government, 1993). This factor was only updated in 2006 (Italian Government, 2006), imposing an average conversion efficiency of 0.4, which corresponds to an $f_{P,el}$ of 2.5, and subsequently in 2009 (Ministero dello sviluppo economico, 2009), where the value of $f_{P,el}$ was further reduced to 2.17. Finally, in 2015 (Ministero dello sviluppo economico, 2015), for the first time in Italy the total factor was divided into two shares: $f_{P,nren,el}$ = 1.95 and $f_{P,ren,el}$ = 0.42. This detailed analysis of the situation in Italy may be repeated for different European countries, generating results in line with the Italian ones, which can be summarized in the following critical points:

- The primary energy factors imposed by political laws are in strong misalignment with the same factors evaluated considering the actual energy balance of the country.
- A constant and monitored updating of the factors is necessary for a correct evaluation of the energy performance of buildings.
- The political choice of primary energy factors could drive the adoption of some technologies over others.

Following the same approach applied to Italy, the results of the EN 17423:2020 standard for the year 2019 applied to 11 European countries were compared with the electrical primary energy factors adopted by the individual national legislations (Output 1.1 vs Output 1.2 and Output 1.3 of the methodological framework of **Figure 1**).

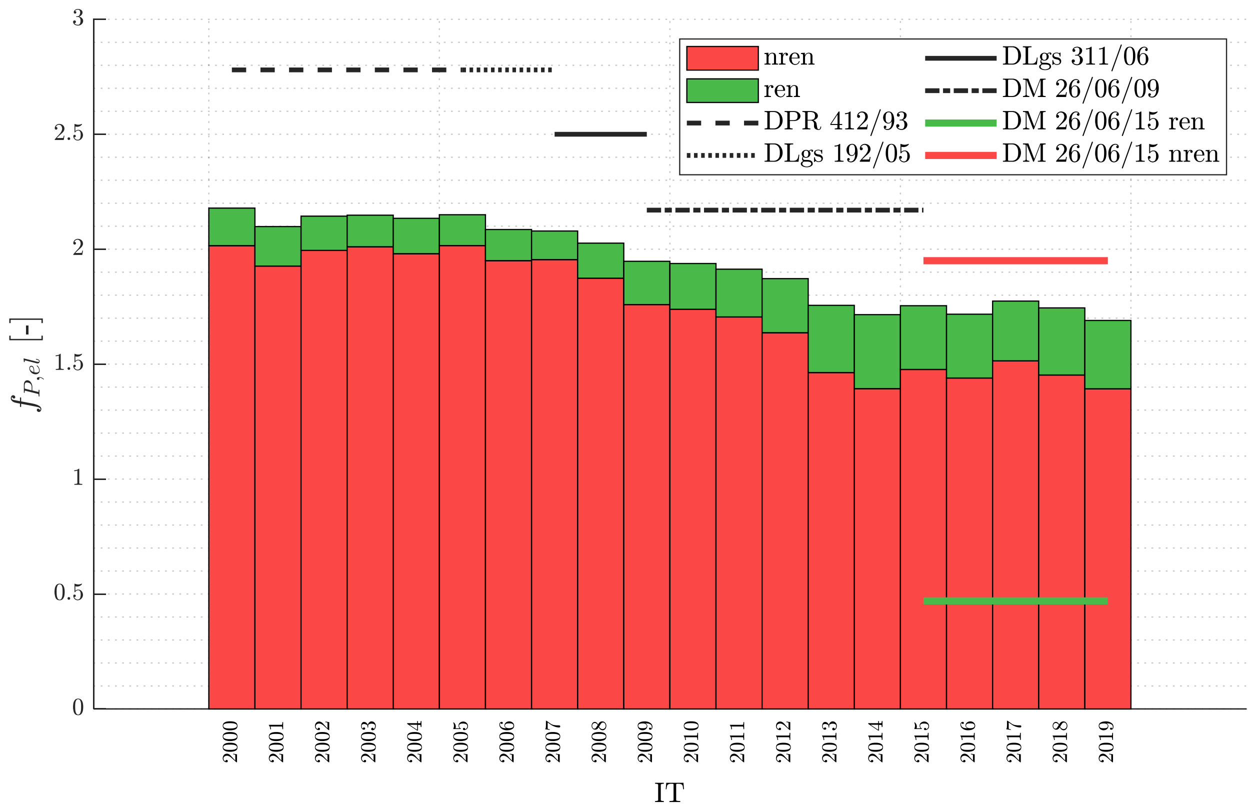

Figure 6 - Comparison of Italian $f_{P,el}$ according to EN 17423:2020 and to national legislation.

Table 5 shows that in most cases legislations propose only total factors. Only France, Germany, Italy and Spain make exceptions. In these countries the current laws in force allow a distinction between renewable and non-renewable primary energy shares.

Among the countries, the Norwegian legislation states that "*Norwegian electricity production is almost exclusively based on renewable energy and fossil fuels are to be phased out from buildings, primary energy factors are not used in the regulations*". This statement is also supported by the numerical values evaluated in this paper.

From the analyzes carried out, it is evident that some national regulations apply factors far from those assessed by EN 17423:2020. This is the case of UK, adopting a total factor of 3.0 (indicating that the overall conversion efficiency of 0.33), an unrealistic value to date; on the contrary, the $f_{P,el}$ of the French legislation is consistent with the analyzes of this work since the energy mix of France has not undergone major variations in the last 20 years. For all the other countries a difference is evident, but above all the absence of a regulated renewable and non-renewable factors emerges. The differences between the PEFs calculated by applying the methodology of the EN 17423:2020 standard and the PEFs established by political laws is evident and should give pause on how political choices significantly influence the energy development of a country.

Table 5 additionally reports the electrical primary energy factors suggested by EN ISO 52000-1:2017, used as a European average reference and sometimes adopted for preliminary large-scale analyzes. The primary energy assessments carried out within the European Tabula project adopt the values suggested by EN ISO

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52000-1: 2017, as reported in the final row of **Table 5**.

Table 5 - A Comparison of $f_{P,el}$ evaluated by EN 17423:2020 for the year 2019 and $f_{P,el}$ currently in force in some European countries.

		EN 17423:2020 (reference year 2019)			National regulation			
Country	**Code**	$f_{P,nren}$	$f_{P,ren}$	$f_{P,TOT}$	$f_{P,nren}$	$f_{P,ren}$	$f_{P,TOT}$	**REF**
Denmark	DK	0.87	0.54	1.40	-	-	1.9	(Engelund et al., 2020)
France	FR	2.21	0.22	2.43	2.30	0	2.30	(Ministry of Ecology Sustainable Development Transport and Housing of France, 2012, 2020)
Germany	DE	1.38	0.37	1.75	1.80	1.00	2.80	(Schettler-Köhler et al., 2016)
Greece	EL	1.91	0.27	2.18	-	-	2.90	(Ministry of Environment and Energy of Greece, 2017)
Italy	IT	1.39	0.30	1.69	1.95	0.42	2.42	(Costanzo et al., 2016)
Netherland	NL	1.61	0.15	1.77	-	-	2.56	(van Cruchten, 2020)
Norway	NO	0.24	0.89	1.13	-	-	-	(Brekke & Karstad Isachsen, 2020)
Slovenia	SI	1.56	0.32	1.88	-	-	2.5	(Šijanec Zavrl et al., 2016)
Spain	ES	1.61	0.35	1.97	2.007	0.396	2.403	(Ministries of Industry, Energy and Tourism and Ministry of Public Works of Spain, 2016)
Sweden	SE	0.81	0.63	1.44	-	-	1.8	(The Housing Authority of Sweden, 2020)
United Kingdom	UK	1.48	0.28	1.76	-	-	3.07	(Department of Energy and Climate Change, 2014)
EN ISO 52000-1	EU	1.66	0.30	1.96	2.30	0.20	2.50	(CEN – European Committee for Standardization, 2017b)

5.2 Primary energy needs for European reference buildings (Outputs 2.x)

After considering the temporal evolution of $f_{P,el}$ for different European countries through the application of the EN 17423:2020 standard, their application on the energy performance of buildings is now analyzed. This section reports the primary energy (PE) results, expressed in kWh/(m^2·a), obtained on the 37 case studies

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reported in **Table 4** (Outputs 2.x of the framework of this study, see **Figure 1**).

Figure 7 represents PE values for the selected case studies, divided into 4 building types: SFH in **Figure 7a**, AB in **Figure 7b**, MFH in **Figure 7c**, TH in **Figure 7d**. For each country analyzed, three results were reported in terms of PE, obtained from the three sets of $f_{P,el}$ applied:

- "**2019**" indicates the primary energy (PE) calculated by applying the $f_{P,el}$ according to EN 17423:2020 in the 2019 analysis year.
- "**reg**" means that PE is calculated according to the proposed factors of the national regulations.
- "**52000**" indicates that PE is evaluated through the application of EN ISO 52000-1:2017.

Every Primary Energy (PE) result in this section has been evaluated adopting Equation (6):

$$PE = \left(E_{el,del}\right) \cdot f_{P,el} \left[\frac{kWh}{m^2 \cdot a}\right] \text{ where } f_{P,el} = \begin{cases} f_{P,el,2019} & \text{according to EN 17423:2020} \\ f_{P,el,reg} & \text{according to national regulation} \\ f_{P,el,52000} & \text{according to EN ISO 52000-1:2017} \end{cases} \quad (6)$$

Where the calculation methodology allowed it, the results were divided into renewable (green) and non-renewable (red) shares. When only the total value was available, the result has been reported in gray. Additionally, delivered energy value associated with each case study building was also reported (black line), expressed as kWh/(m^2·a) of electricity required for heating and ventilation needs.

The results represented in **Figure 7** allow for some important considerations relating to the energy performance of buildings. First, three different evaluation methodologies are compared for each country: in some countries the application of the different methodologies lead to similar results. This is for example the case of Spain, Greece and France, where the current legislation in terms of PEFs correctly describes the energy balance of the nation. In other countries, however, the application of each method for PE evaluation leads to conflicting results: this happens in Germany, Denmark and the Netherlands. Generally, it can be said that PE evaluated by EN ISO 52000-1:2017 tend to always be the highest, thus overestimating the real primary energy needs. Differently, the application of EN 17423:2020 using Eurostat energy balances generally produces lower results and, in any case, corroborated by a calculation methodology. The values applied following national regulations, on the other hand, are often difficult to justify and are not supported by objective physical considerations. This comparison leads to important critical issues in the correct evaluation and comparison of European buildings. A shared method is therefore increasingly necessary not only to achieve more reliable results in terms of energy performance, but also to make EU energy policy decisions.

Further considerations can be made by comparing different countries. SFH building type is characterized by similar delivered energy values across a significant number of countries considered (IT, DK, EL, UK, FR), which correspond to different primary energy results. This consideration makes it possible to objectively identify the performance of a European building according to its country of origin. For example, an Italian SFH, with the same delivered energy of a Greek SFH, will perform better in terms of primary energy, when considering PEFs according to EN 17423:2020. Also, a German and a French MFH would appear to have similar performance if considering their respective regulation performances. However, the application of EN 17423:2020 greatly rewards the performance of the German building. A similar consideration can be made by considering a Dutch and a Slovenian AB. Again, these considerations are clear evidence of how a comparison between European buildings is almost impossible if the same boundary conditions are not applied regarding the evaluation of primary energy factors.

Finally, several assessments can be advanced by analyzing the primary renewable energy shares associated with buildings. Taking into consideration a Dutch and a German TH, whose delivered energy and total PE is comparable, it is possible to state that the German building is better exploiting renewable sources, considering EN 17423:2020 as calculation approach.

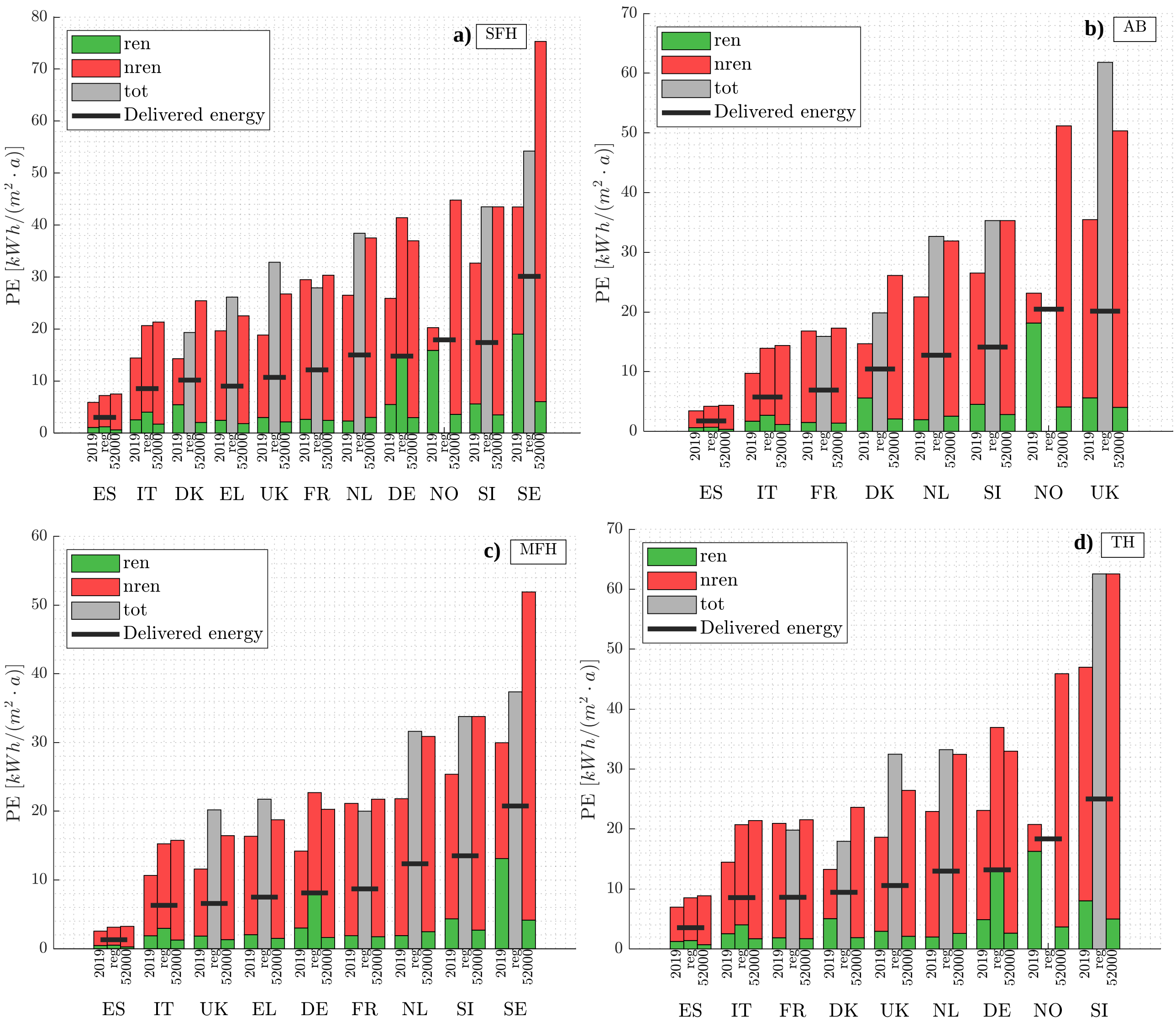

Figure 7 - Primary energy (PE) needs for 4 building types: SFH – Single Family House (**7a**), AB – Apartment Block (**7b**), MFH – Multi-Family House (**7c**), TH – Terraced House (**7d**). Comparison of the results obtained by applying three calculation methodologies: EN 17423:2020 (applied for the analysis year "2019"), national regulation ("reg") and EN ISO 52000-1:2017.

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6. Discussion and conclusions

From the results achieved in this work relevant considerations on the current tools for assessing primary energy needs for European buildings can be done. In particular, the EN 17423:2020 standard was taken into consideration for the calculation of the electrical primary energy factor. The application of the standard to the energy balances of 11 European countries confirmed the variability over time of $f_{P,el}$, demonstrating the importance of a continuous update for an accurate evaluation of the conversion factor. Furthermore, conversion factors calculated using the EN 17423:2020 standard were compared with the average ones proposed at European level (EN ISO 52000-1:2017) and, where possible, with the factors established by individual national regulations fixed by governments. The following results were achieved:

- The electrical primary energy factors have a variable trend in time and space (national territories), which cannot be neglected for primary energy analysis. In this work, the variability over time was studied annually, while the variability in space according to the national borders of European countries.
- The use of current PEFs depends on political choices that do not reflect the actual condition of energy generation and production of European countries. This consideration derives from the comparison between the PEFs of national legislation with those assessed through energy balances by applying EN 17423:2020 (see **Table 5**). Although it cannot be applied to all states, this discrepancy is evident for the majority of the states analyzed.
- National policies should monitor national energy flows more frequently to apply more accurate primary energy assessments. This approach should also be regulated on a European scale, to use a unified method of data collection and consequent calculation of PEFs. Thus, generating comparable and representative results of the individual energy conditions of the member states.
- The application of EN 17423:2020 produces reliable results, correctly describing the energy transition policies adopted by individual countries. Compared to the current uses of PEFs for assessing the performance of buildings, based on individual national regulations, the method proposed and applied in this work demonstrates an important step forward. Using a rigorous and repeatable method, as well as shared and comparable input data (Eurostat Energy Balances), the results obtained overcome the negligence and omissions of the PEFs declared in the national regulations.

Furthermore, this study explored the results of a first application of the conversion factors based on European reference buildings, evaluating and comparing the annual primary energy need for space heating with different methods. The results achieved can be summarized as follows:

- The evaluation of the PE using the conversion factors of EN 17423:2020 allowed a comparison of similar buildings belonging to different European countries.

- The method proposed in this work can be the starting point for the application of an energy certification of buildings at European level.

The results achieved in this paper represent an important milestone for the dissemination and adoption of PEFs for the regulation of European buildings energy performance in the light of harmonizing the European policy on highly performing buildings. In addition, the outcomes of the work represent a starting point for scientific research applications in the sector. The future developments of this work will in fact be focused on the analysis of conversion factors at lower timesteps. Further development of this study will focus on the analysis of monthly, daily and hourly conversion factors, to define dynamic primary energy factors in a detailed space and time boundaries.

Appendix

Table A1 – $f_{P,el}$ values from 2000 to 2019 according to EN 17423:2020

Country		Share	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
France	FR	ren	0.153	0.165	0.139	0.131	0.130	0.113	0.127	0.134	0.143	0.140	0.148	0.130	0.163	0.188	0.188	0.178	0.188	0.176	0.217	0.217
		nren	2.470	2.429	2.490	2.500	2.507	2.563	2.532	2.506	2.471	2.526	2.484	2.511	2.429	2.356	2.377	2.382	2.305	2.323	2.231	2.213
Greece	EL	ren	0.085	0.062	0.072	0.105	0.102	0.108	0.126	0.077	0.093	0.126	0.165	0.132	0.163	0.241	0.205	0.240	0.233	0.222	0.268	0.271
		nren	2.537	2.568	2.517	2.409	2.417	2.415	2.326	2.423	2.368	2.537	2.260	2.254	2.216	2.056	2.159	1.939	1.764	1.951	1.942	1.910
United Kingdom	UK	ren	0.025	0.022	0.026	0.023	0.029	0.033	0.038	0.042	0.048	0.056	0.054	0.077	0.090	0.117	0.144	0.182	0.182	0.225	0.250	0.279
		nren	2.503	2.538	2.519	2.532	2.455	2.448	2.452	2.389	2.322	2.257	2.238	2.196	2.183	2.100	1.982	1.853	1.740	1.623	1.539	1.482
Germany	DE	ren	0.063	0.066	0.076	0.074	0.092	0.097	0.107	0.127	0.130	0.137	0.143	0.171	0.196	0.209	0.227	0.266	0.267	0.311	0.329	0.371
		nren	2.398	2.447	2.443	2.440	2.359	2.302	2.273	2.221	2.175	2.143	2.077	1.967	1.951	1.878	1.811	1.682	1.655	1.523	1.477	1.381
Spain	ES	ren	0.162	0.213	0.145	0.217	0.187	0.157	0.183	0.199	0.207	0.260	0.335	0.301	0.304	0.400	0.401	0.343	0.369	0.303	0.358	0.355
		nren	2.328	2.100	2.247	2.040	2.015	2.324	2.274	2.051	2.020	2.347	1.280	1.726	1.877	1.498	1.488	1.557	1.624	1.803	1.668	1.610
Netherlands	NL	ren	0.015	0.015	0.017	0.019	0.026	0.032	0.037	0.039	0.048	0.055	0.051	0.060	0.062	0.066	0.069	0.087	0.096	0.119	0.129	0.154
		nren	2.083	2.115	2.101	2.102	2.067	2.034	1.995	1.980	1.950	1.877	1.856	1.830	1.863	1.863	1.903	1.887	1.817	1.741	1.715	1.612
Slovenia	SI	ren	0.313	0.301	0.248	0.214	0.285	0.236	0.239	0.216	0.277	0.358	0.334	0.262	0.295	0.352	0.456	0.296	0.335	0.286	0.331	0.321
		nren	1.738	1.836	1.992	1.982	1.738	1.811	1.866	1.997	1.786	1.473	1.527	1.767	1.662	1.509	1.236	1.613	1.517	1.641	1.534	1.557
Italy	IT	ren	0.164	0.172	0.149	0.138	0.154	0.134	0.135	0.124	0.152	0.188	0.199	0.208	0.235	0.292	0.322	0.277	0.278	0.260	0.292	0.297
		nren	2.015	1.927	1.995	2.011	1.980	2.016	1.950	1.955	1.874	1.759	1.739	1.705	1.637	1.463	1.393	1.477	1.440	1.514	1.453	1.393
Denmark	DK	ren	0.127	0.129	0.147	0.168	0.199	0.202	0.182	0.212	0.207	0.211	0.244	0.304	0.326	0.361	0.427	0.459	0.421	0.490	0.467	0.535
		nren	1.927	1.880	1.834	1.728	1.633	1.621	1.663	1.604	1.610	1.577	1.445	1.324	1.300	1.191	1.070	1.046	1.081	0.912	0.970	0.869
Sweden	SE	ren	0.536	0.523	0.449	0.375	0.422	0.504	0.437	0.470	0.502	0.509	0.489	0.532	0.612	0.523	0.568	0.682	0.563	0.596	0.567	0.631
		nren	1.218	1.286	1.451	1.625	1.519	1.288	1.450	1.345	1.252	1.161	1.202	1.112	0.874	1.110	1.025	0.766	1.017	0.925	0.997	0.812
Norway	NO	ren	0.984	0.909	0.951	0.877	0.868	0.965	0.912	0.948	0.966	0.917	0.847	0.873	0.943	0.897	0.924	0.919	0.933	0.931	0.916	0.887
		nren	0.031	0.202	0.106	0.274	0.295	0.073	0.192	0.108	0.068	0.159	0.356	0.288	0.113	0.217	0.154	0.170	0.139	0.144	0.178	0.244

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