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Building for a Zero Carbon future: trade-off between carbon dioxide emissions and primary energy approaches

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Abstract

Growing urbanization is driving urban policy makers to adopt sustainable practices aimed to limit the environmental impact of buildings which are responsible for an estimated 36% of climate-changing gas emissions in European cities. In order to meet the ambitious emission reduction targets set by the EU it is essential to develop policy for CO_2 emissions saving. This work investigates the regulations of European countries that introduce carbon compliance requirement as implementation of the EPBD such as UK, Ireland, Austria and some Eastern European countries. With reference to the typical consumption pattern of an Italian home, the paper analyses the current limits of primary energy, RES requirements and CO_2 emissions, investigating the relations between EP_{nren} and carbon dioxide emissions levels.

Keywords: Carbon dioxide emissions; Primary energy; Zero carbon; Energy hub; nZEB buildings; RES.

1. Introduction

During the Conference of the Parties held in Paris (COP21) [1], Member States set out a global plan to put the

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world on track with two main objectives: (1) to avoid dangerous climate change by keeping global warming well below 2°C above pre-industrial levels and (2) to pursue an effort to limit the temperature rise to 1.5°C. This ambitious long-term objective will require the start of “zero GHG emission” from a period between 2020 and 2030.

The most recent report of Intergovernmental Panel on Climate Change (IPCC) [2], published in 2014, estimates that through technical measures approximately 29% of emissions could be avoided in residential and commercial building sector in 2020 and 40% in 2030. Governments are paramount in order to create and coordinate buildings sectors’ responses and must be able to identify and encourage synergies between buildings adaptation to climate change and GHG emissions mitigation.

In Europe, the building sector is responsible for huge energy consumption and results as one of the most influent sectors in which reduction action should be regulated. Buildings account for approximately 40% of global energy consumption, taking into account only the operational life period, and 36% of CO_2 emissions [3] and the total CO_2 emissions achieve 54 $kgCO_2/m^2$. Moreover, considering that almost 70% of the existing building stock will still be used in 2050 and that it is expected a 25% increase in building stock, a long-term vision is needed to align with future challenges because without any reduction regulation CO_2 emission could be double or triple by 2050.

From this point of view, the updating of the European directives offers a possibility to develop actions aimed at lower energy consumption and a reinforced use of renewable energy sources (RES). On March 2011, the European Commission adopted a "Roadmap for moving to competitive low carbon economy" with reference to 2050, identifying from this perspective the need for greater attention to energy efficiency [4]. In this document, the European Commission has established a long-term goal of reducing CO_2 emissions for the building sector by 88-91% by 2050 compared to 1990 levels.

The Directive 31/2010 / EU of 19 May 2010, Energy Performance of buildings (EPBD recast) [5] deals with the topic of "energy performance" understood as the calculated or measured energy quantity needed to meet the energy needs associated with normal building use; it does not establish particular constraints on carbon production. Article 2 of the EPBD recast requires that starting from 2020 the new buildings must be nearly zero energy buildings (nZEB), encouraging self-generation of energy and the use of RES. It also states that "it is necessary to set up measures to increase the number of buildings that not only meet the minimum requirements in force but have an even higher energy performance, thereby reducing both energy consumption and carbon dioxide emissions. To this end, Member States must draw up national plans to increase the number of nearly zero energy buildings”.

With the aim of achieving the standard ambitions introduced by the definition of nZEB, Member States have announced several parameters, both in terms of quality and quantity. But, only few states such as United Kingdom, Ireland, Austria, and Romania introduced performance limits directly related to the concept of climate-altering anthropogenic emissions introduced by COP21; in these countries, the threshold values are the maximum annual GHG emission measured by $kgCO_2$ per square meter. While Luxembourg, Bulgaria, France, and Spain started to propose the introduction of carbon compliance values.

2. Carbon requirements

2.1. Zero Carbon Homes in the United Kingdom

United Kingdom policies can be considered as a major regulation reference regarding carbon reduction in the construction sector. This is evidenced by various legally limiting objectives and standards, among which the Climate Change Act 2008 (CCA) [6] can be considered one of the most important. A strategy for achieving a reduction of carbon emissions by 80%, compared to 1990 levels, by 2050, with a reduction of at least 34% by 2030, was set out in the Carbon Plan published in December 2011[7]. The policy introduced in the UK for zero carbon buildings is part of the government's broader strategy to achieve the goal of the CCA, while at the same time contributing to addressing other important issues, including energy security and energy poverty.

The Energy Performance of Buildings Regulations 2012 (SI 2012/3118) in England and Wales [8] required the assessment of the "identification and analysis of the impact of carbon emissions on the environment deriving from buildings with low levels of energy efficiency". In December 2006 the government established that from 2016 all new homes would be “zero carbon” and introduced the Code for Sustainable Homes, against which the sustainability of new homes could be rated. This commitment was affirmed in the policy statement “Building a Greener Future” in 2007 [9].

Until 2006 the UK's building regulations were based on minimum energy efficiency standards, but following the EPBD, the requirements have been revised and a maximum level of associated CO_2 emissions has been defined. The new legislation requires, in fact, to reduce all on site carbon dioxide emissions due to energy consumptions of all new buildings, since 2016, through various measures. This includes the energy used to provide space heating and cooling, hot water and lighting [10]; but it does not take into account the unregulated emissions due to the use of the building such as emissions from cooking and from appliances, such as computers and tv.

The criteria of CO_2 emission limits are described in detail in the "Part L1A" section of UK's building regulations [10]. The legislation states that: the calculated Dwelling Fabric Energy Efficiency (DFEE) rate, expressed as kWh/m^2 per year, must not be greater than 1.15 times the Target Fabric Energy Efficiency (TFEE) rate. Additionally, the calculated rate of CO_2 emissions the Dwelling CO_2 Emission Rate (DER), expressed in $kgCO_2/m^2$ must not be greater than the value of the Target CO_2 Emission Rate (TER), calculated having the same dimensions and the same shape but technical characteristics established by reference values.

In order to facilitate the implementation of this policy and to take day-to-day operational responsibility for achieving the Government's target the need for a new organization was identified [11]. In 2008, the Zero Carbon Hub (ZCH) was set up as a non-profit organization in order to investigate the methods for achieving zero carbon homes starting from 2016. The main objectives of this organization were to create trust in change, to reduce the risk and the obstacles, and to spread a practical guide. Zero Carbon Homes methodologies of design approach have been published and clarified, by ZCH and the limits of energy requirements and of carbon dioxide emissions in the atmosphere have been published (Table 1).

Table 1. On-site performance targets proposed for Zero Carbon Homes [11].

Built form	FEES [kWh/m^2.year]	Carbon Compliance [$kgCO_2/m^2$.year]
Detached house	46	10
Semi-detached houses	46	11
End of terrace house	45	11
Apartment blocks (up to 4 stories)	39	14

In Table 1, the Fabric Energy Efficiency Standard (FEES) is the proposed maximum space heating and cooling energy demand for zero carbon homes. While, according to the above aforementioned DER the Carbon Compliance limit is the maximum permitted amount of CO_2 arising from heating, cooling, hot water use, lighting, and ventilation. The definition of this standard was gradual and developed in continued collaboration with stakeholders and Government. The concept of "Allowable Solutions" was proposed by Government in 2009. A first solution contemplates that a lower on-site emissions target could be set for house builders by paying into a fund an agreed fee per $kgCO_2$ to offset emission over a 30 year period [12]; this measure allows to knock down unavoidable emissions and provides a national carbon abatement fund dedicated to carbon-saving projects. Other solutions were proposed, mainly consisting in the possibility of performing on-site implementations: extension of green areas, contribution to the development of local energy systems (i.e. district heating or high efficiency public lighting) or interventions on existing buildings in order to save energy (i.e. envelope insulation).

The report *Zero Carbon Strategies for tomorrow's new homes* [11], published in 2013, proposed the strategies for reducing CO_2 and achieving legislative constraints.

Three steps have been developed to classify a Zero Carbon Home:

- High standards of DFEE in order to reduce energy demand and comply FEES standard (Table 1).
- Through an integrated mix of fabric measures and appropriate low-carbon heat and power technologies (i.e. exploitation of solar and/ or wind energy and high efficiency energy systems) the builders must drive emissions less than or equal to the Carbon Compliance values (Table 1).
- Any residual CO_2 emissions after having reached the limits required in points 1 and 2 must be reduced to zero by the use of allowable solutions.

The goal is to ensure the achievement of the proposed Carbon Compliance limit 11 $kgCO_2/m^2$ per year that is a reduction of around 17 $kgCO_2/m^2$ per year compared with a similar house in accordance with the 2006 standard.

2.2. Carbon requirements for homes in other European countries

Besides United Kingdom, also other European States have introduced CO_2 requirements for the building sector. The new legislation in Ireland (January 2011) has introduced the concept of nZEB, in line with the official UK's documents. In Ireland's definition of NZEB the typical performance standards defined for dwellings are set at 45 kWh/m^2 per year and 10 kg/m^2 per year for primary energy consumption and CO_2 emissions respectively; moreover 22% of energy used by building should be covered by renewable energy sources (RES), produced on site or off site. [13]. In Austria [14], the implementation of the EPBD was entrusted to the Austrian Institute of Construction Engineering through the drafting of the OIB Guidelines. This document stated total primary energy ($EP_{,tot}$) and carbon emissions levels distinguish between new construction and renovation action; for residential buildings the CO_2 (refers to 2020) will be 24 kg/m^2 and 269 kWh/m^2 per year of $EP_{,tot}$. The Romanian legislation has also introduced targets in relation to the emission of CO_2, in 2014 the Government presented the real estate growth plan in which energy consumption was close to or equal to zero. The limit proposed there for residential buildings are: 115 kWh/m^2 per year of Primary Energy consumption and 31 kg/m^2 per year of carbon dioxide emissions, this levels refers to 2018 and will be more restrictive in 2020 [15]. Also, Bulgaria, France, Luxemburg, and Spain declared that they are developing national plans that take into account carbon dioxide emissions reduction factor in the environment.

3. Trade-off between carbon dioxide emissions and primary energy in Italian regulation

In Italy, the mean value of CO_2 emissions in the building sector, residential and not residential, is around 41 kgCO_2/m^2 [16]. The current legislation on building energy efficiency is described in DM 26/2015 [17]; which sets the minimum requirements and the characteristic of a reference building. Italian current legislation defines the energy performance of the building through two main factors: global not-renewable performance index ($EP_{,gl,nren}$) and technical system performance (η_x) comparing the efficiency of the system with reference values. Moreover, D.L 28/2011 [18] promotes the use of renewable energy and it provides that 50% of domestic hot water (DHW) energy demand should be supplied with renewable energy source (RES). It states also that 50% of the sum between heating, cooling and DHW demands has to be supplied by RES.

A numerical approach was used to evaluate the Italian primary energy limit in contrast with the carbon emissions. Values of primary energy and carbon emissions were calculated trough exemplary cases and then compared with the aim of understand relation between them. An energy hub was defined and coupled to two different sets of energy demand. Seasonal consumption patterns of a typical single house in Italy were defined as show in Table 2 according to existing statistical data [19-20]. The value assumed refers to 100 m^2 and are generalized by way of example.

Table 2. Seasonal energy demand for a typical Italian home of 100 m^2.

Type	Set_1 [kWh]	Set_2 [kWh]
Space heating - E_{out}^{h}	5,000	5,000
Space cooling - E_{out}^{c}	2,000	0
Domestic hot water - E_{out}^{dhw}	2,000	2,000
Electricity - E_{out}^{el}	3,500	3,500

3.1. The methodology

The energy hub tool (EH-tool) [21] helps to understand the behavior of complex, highly interlinked combinations of various energy supply system. The energy hub methodology was here used to analyze different theoretical scenarios that consider several energy supply systems and energy demands. In particular, the aim of this work is to estimate the seasonal CO_2 production and the seasonal primary energy consumption of a home characterized by the above reported energy demand reported in Table 2.

The EH-tool is composed by three sections: the energy inputs, the energy convertes and the end-uses. The first section represents the set of energy sources (e.g. natural gas, biomass, etc.), while the last one represents the set of the end-uses demand (e.g. space heating, space cooling, etc.). The energy converters and the scheme of the EH-tool considered in the presented work for homes are reported in Table 3 and in Fig. 1 respectively.

Table 3. List of energy converter used in the energy hub.

Energy convert	End-uses demand	Energy convert	End-uses demand
Gas Boiler (GB)	Heating, DHW	Chiller (C)	Cooling
Biomass boiler (BB)	Heating, DHW	Solar Collector (SC)	DHW
District Heating (DH)	Heating, DHW	Photovoltaic (PV)	Electricity
Heat pump (HP)	Heating, DHW	Energy from grid (EG)	Electricity

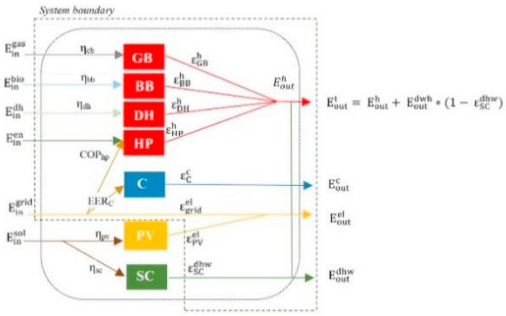

Fig. 1. Schematic of the theoretical energy hub for Italian homes.

The scheme in Fig. 1 can be expressed in mathematical form to evaluate the energy inputs as a function of the end-uses demand as

$$
\begin{cases}
E_{in}^{gas} = \dfrac{E_{out}^{h} * \varepsilon_{GB}^{h}}{\eta_{GB}} & [\mathrm{kWh}] \\
E_{in}^{bio} = \dfrac{E_{out}^{h} * \varepsilon_{BB}^{h}}{\eta_{BB}} & [\mathrm{kWh}] \\
E_{in}^{dh} = \dfrac{E_{out}^{h} * \varepsilon_{DH}^{h}}{\eta_{DH}} & [\mathrm{kWh}] \\
E_{in}^{sol} = \dfrac{E_{out}^{dhw} * \varepsilon_{SC}^{dhw}}{\eta_{SC}} + \dfrac{E_{out}^{el} * \varepsilon_{PV}^{el}}{\eta_{DH}} & [\mathrm{kWh}] \\
E_{in}^{grid} = \dfrac{E_{out}^{h} * \varepsilon_{HP}^{h}}{\mathrm{COP}_{HP}} + \dfrac{E_{out}^{c} * \varepsilon_{C}^{c}}{\mathrm{EER}_{C}} + E_{out}^{el} * \varepsilon_{grid}^{el} & [\mathrm{kWh}]
\end{cases}
\tag{1}
$$

where ε represents the ratio between the energy on a line and the total energy at the output and η, COP, EER are the energy efficiency of each energy converters. Parameters η, COP and EER were fixed according to DM 26/06/2015 “minimum requirement” Annex A [17].

Since ε, η, COP and EER parameters have a physical meaning, they must fulfil constraints that were considered as follow

$$
\begin{cases}
\varepsilon_{GB}^{h} + \varepsilon_{BB}^{h} + \varepsilon_{DH}^{h} + \varepsilon_{HP}^{h} = 1;\ \varepsilon_{C}^{c} = 1 \\
0 \le \varepsilon_{SC}^{dhw} \le 0.5 \\
0 \le \varepsilon_{PV}^{el} \le 0.5 \\
\eta,\ \mathrm{COP},\ \mathrm{EER} > 0
\end{cases}
\tag{2}
$$

Another constrain, Eq. (3), was added to take into account the link between the space heating demand and the DHW demand that is not covered by solar energy

$$E_{out}^{h} = E_{out}^{space\ heating} + E_{out}^{dhw} * \left(1 - \varepsilon_{SC}^{dhw}\right) \tag{3}$$

System of equations (1) can be solved using $[\varepsilon_{GB}^{h};\ \varepsilon_{BB}^{h};\ \varepsilon_{DH}^{h};\ \varepsilon_{SC}^{dhw};\varepsilon_{PV}^{el}]$ as unknowns if the scope of the calculation is the design of the system. In our case $[\varepsilon_{GB}^{h};\ \varepsilon_{BB}^{h};\ \varepsilon_{DH}^{h}]$ and $[\varepsilon_{SC}^{dhw};\varepsilon_{PV}^{el}]$ were considered as parameters and varied within the range [0:0.25:1] and [0:0.25:0.5] respectively. More than 100 theoretical combinations of the energy hub configurations were thus obtained for each set of consumption pattern.

Once the energy inputs $[E_{in}^{gas};\ E_{in}^{bio};\ E_{in}^{dh};\ E_{in}^{sol};E_{in}^{grid}]$ were evaluated coupling Eqs. (1-3) with data reported in Table 3, kg of CO_2 emissions and primary energy consumption (renewable and not renewable) were calculated according to conversions factor reported in UNI-TS 11300 parts 4 and 5 respectively. The conversion factors for primary energy calculation and for carbon dioxide calculation are summarized in Table 4. The primary energy factors are published in DM 26/2015, and represent annual average factor, while the K_{CO2} factor respects the value proposed by ENEA [23]. Usually K_{CO2} emissions factor associated with electricity are calculated on the basis of a specific energy mix and influenced by the efficiency of the production, transport and distribution system for electricity energy.

Table 4. Conversion factors for CO_2 emissions (K_{CO2}) and primary energy consumption ($f_{p,ren}$ and $f_{p,nren}$).

Energy input	$f_{p,ren}$	$f_{p,nren}$	$f_{p,tot}$	K_{CO2} [kg CO_2/kWh]
Natural gas	1.05	0.0	1.05	0.1998
Solid biomass	0.20	0.80	1.0	0.0
District heating	1.50	0.0	1.5	0.36
Solar collector	0.0	1.0	1.0	0.0
Photovoltaic	0.0	1.0	1.0	0.0
Electricity from the grid	1.95	0.47	2.42	0.4332

3.2 Results and discussion

Among whole configurations, D.lgs 28/2011 was used to identify which of these configurations respect RES requirements. The calculation was done according to UNI-TS 1330-part 5 and CTI recommendations. Table 5 collects six configurations that can be considered typical of Italian systems, and comply with the current regulation. The six configurations (A, B, C, D, E, F) report different levels of energy consumption and carbon dioxide emissions achieved using technical systems such as: heat pump, biomass boiler and district heating system.

According to the energy needs pattern set_1 (Table 2) adopted it is interesting to note that any setup that involves a large use of gas boiler cannot achieve good performances in terms of $kgCO_2$ and $EP_{,gl,ren}$ and does not comply with current legislation.

Fig. 2 compares consumption of renewable primary energy ($EP_{,gl,ren}$), not renewable primary energy ($EP_{,gl,nren}$) and the amount of carbon dioxide emissions (M_{CO2}) data obtained for all theoretical configurations from the EH-tool. $EP_{,gl,nren}$ and total primary energy consumption ($EP_{,gl,tot}$) values for 105 configurations of set_1 are presented in Fig. 2a; the range of $Ep_{,gl,tot}$ consumption goes from around 60 to almost 200 kWh/m^2, showing a 65% difference between the most efficient EH-tool configuration and less efficient ones. The gap between the cumulative curves of $EP_{,gl,nren}$ and $EP_{,gl,tot}$ are wider for more performing configurations. In contrast, the gap becomes smaller for higher energy consumption solutions that often use a small amount of RES. Generally the points with higher $EP_{,gl,nren}$ represent the configurations that mostly use electricity from the grid to meet the annual thermal energy needs and do not usually use renewable energy, i.e. ε_{PV}^{el} and/or ε_{SC}^{dhw} equal to zero. The lower part of the graph presents configurations with low energy consumption usually exploiting HP or biomass boilers coupled with solar collectors and photovoltaic panels in order to provide a large amount of electricity and thermal energy for DHW.

Table 5. Configurations reliable of set_1.

Name	%RES (H+C+DWH)	%RES (DHW)	ε_{GB}^{h}	ε_{BB}^{h}	ε_{DH}^{h}	ε_{HP}^{h}	ε_{C}^{c}	ε_{PV}^{el}	ε_{SC}^{dhw}	ε_{grid}^{el}	$EP_{,gl,nren}$ (kWh/m^2)	$EP_{,gl,tot}$ (kWh/m^2)	M_{CO2} ($kgCO_2$/m^2)
A	54	66	0	0.75	0.25	0	1	0.25	0.25	0.75	105.5	189.5	21
B	54	74	0	0	0	1	1	0.5	0.5	0.5	88.76	177.6	20
C	71	84	0	1	0	0	1	0.25	0.25	0.75	105.5	189.47	21
D	71	88	0	1	0	0	1	0.5	0.5	0.5	66.4	172.5	11
E	70	80	0	1	0	0	1	0	0	1	103	201	19
F	52	64	0	0	0	1	1	0.25	0.25	0.75	109.4	192.4	24

Moreover, Fig. 2a presents the range of solutions, which comply with current regulations, and denotes some points previously shown in Table 5 (A, B, C). The red points represent the configurations with a percentage of renewable energy at least equal to 60%; this range goes from 60 to 125 kWh/m^2 of $EP_{,gl,nren}$. The points out of range are not complying systems; usually solutions that do not use renewable energy in electricity generation with ε_{PV}^{el} equal to zero.

In Fig. 2b all configurations are reported in relation to their RES share and M_{CO2}. For both consumption patterns, set_1 and set_2, it is shown how for each RES values there is not a unique value of carbon dioxide emissions level; instead, a range of M_{CO2} data can be found. According to the EH-tool configurations used in this case and all hypotheses assumed, it emerges that the carbon compliance limit for Italian legislation should be around 30 kgCO_2/m^2, which is 10 kgCO_2/m^2 more than the carbon compliance value proposed in UK regulations. This difference is mainly due to the different carbon conversion factors established in the two countries. The different consumption patterns characterising different building construction culture also have an influence. Fig. 2c shows the ratio between M_{CO2} and $EP_{,gl,nren}$ consumption for all configurations in set_1 and set_2 conditions and the red points again represent complying configuration. The ratio is compared with the current Italian conversion factors (Table 4) for the different energy carriers; this ratio can be seen as the average conversion factor value of each generated configuration and it is similar to the K_{CO2} factor of natural gas. Fig. 2d shows the percentage change with respect to the maximum value obtained of EP_{nren} and M_{CO2}. It emerges that there is a quite good linear correlation between ΔEP_{nren} and ΔM_{CO2}. With a slope of about 0.9, i.e. a reduction of 12% in EP_{nren} corresponds to a reduction of 18% in carbon dioxide emission (energy supply GB and DH).

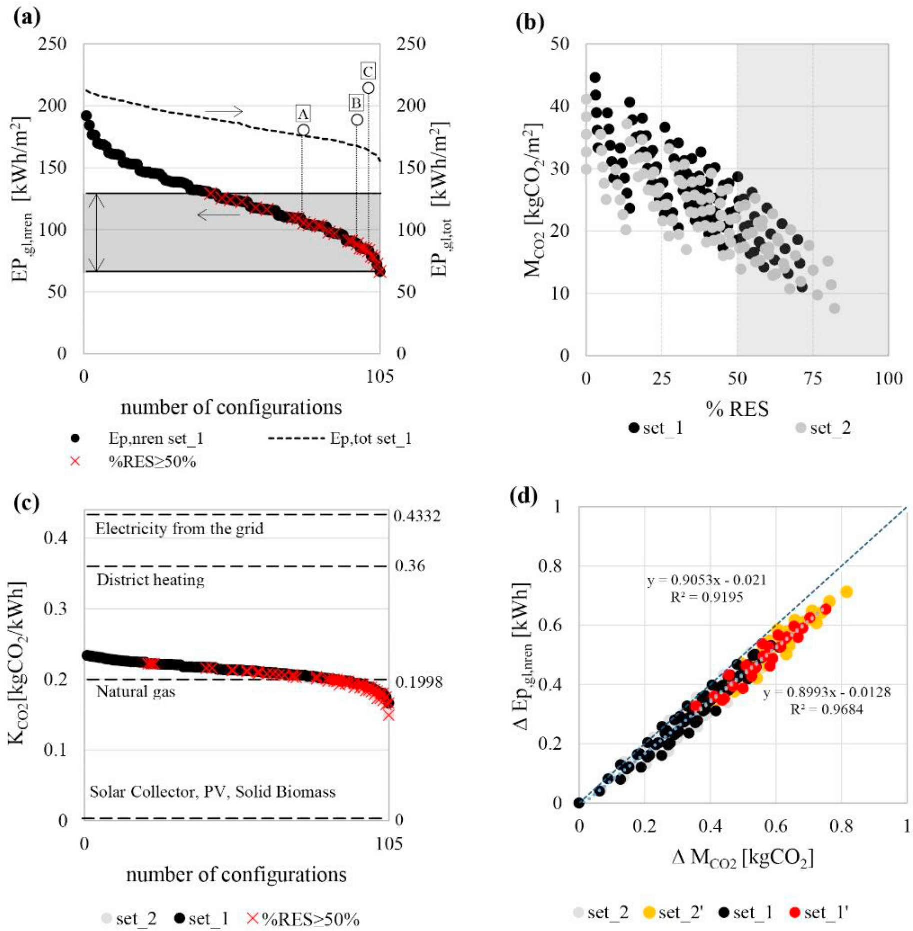

Fig. 2. (a) not-renewable primary energy and total primary energy; (b) RES% and carbon dioxide emissions; (c) Ratio between CO_2 and $EP_{,nren}$; (d) Relation between reduction of carbon dioxide emissions and reduction of primary energy not-renewable.

4. Conclusions

The scientific world is currently studying the challenge of climate change and many studies about carbon emission reduction are being done. Starting from the UK's experiences, this paper analyzes, within the Italian context, different theoretical scenarios of systems usually adopted in homes, estimating primary energy consumption and carbon dioxide emissions. The study intends to start a discussion around the relation between primary energy requirements and carbon dioxide reduction requirements.

This work demonstrated that there is, generally, a correspondence between the reduction of not-renewable energy sources use and the reduction carbon dioxide emissions (growth in the share of RES corresponds to a decrease in the carbon dioxide emissions rate). However, it was shown that different amounts of carbon dioxide emissions can correspond to the same percentage of RES. This relation could change if different emissions factors are used. In fact, it is also important to notice that different countries will set out different carbon compliance values because each country is characterized by a different energy mix and also different consumption patterns. Further studies should consider carbon dioxide arising not only from regulated emissions but also from unregulated ones (i.e. cooking and plug-in appliances). Furthermore, in order to investigate the problem more in depth, future studies may consider embedded carbon dioxide emission in buildings (taking into account, CO_2 emissions from production and installation of systems, construction materials, transport etc.).

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