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Interpolating functions for CO_2 emission factors in dynamic simulations: the special case of a heat pump

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Abstract

The decarbonization strategy implies a strong reduction of greenhouse gas emissions in Europe. The use of heat pumps as generation systems for space heating is increasing together with the increase of renewable energy sources and is also increasing the attention paid to dynamic simulations of heat pumps as well as greenhouse gas emissions. In the present study, a simplified model to determine the hourly emissions of carbon dioxide of a device connected to the Italian power grid is investigated, and an interpolating function for each year, as well as concerning average conditions, is introduced, as a valid tool for deciding the utilization strategies of a heat pump to reduce carbon dioxide emissions in the atmosphere, or, more in general, to evaluate the CO_2 emissions when a common electric device is connected to the grid. The obtained results are applied to the special case of a residential heat pump displaying a particularly good agreement, with a maximum error of 1.8% for the heating season and 1.4% for the cooling one.

Keywords: dynamic CO_2 emissions; renewable energy sources; heat pumps; decarbonization.

1. Introduction

In the European Union (EU), buildings are responsible for about 40% of the overall energy demand and produce 36% of the greenhouse gas emissions [**1, 2**]. As stated in the Integrated National Energy and Climate Plan (2019), Italy agreed to the EU approach to promote a Green New Deal, committing to accelerate the decarbonization process reducing greenhouse gas emissions by 2030 of at least 55%, and to decarbonize the EU's building stock by 2050 [**3, 4**].

Space conditioning, heating and cooling play an important role in the whole energy demand in Europe. Heat pumps, as generation systems for space climatization, are becoming increasingly utilized in the European context [**5**]. The wide use of heat pumps, both air-source [**6, 7**] and geothermal [**8, 9**], for heating and cooling, in addition to the electrification of transport and other electric services, leads to the fastest growth of all the electricity sector. Moreover, electrification of the household sector is becoming an opportunity to replace part of the fossil fuel usage with renewable energy (RES), mainly photovoltaic panels. RES share in Europe (EU-27) is increasing from 14.4% in 2010 to 19.7% in 2019 [**10**]; moreover, during the Covid-19 pandemic, as reported in the IEA World energy outlook 2020 [**11**], the energy demand from renewable energy sources increased, while on the contrary the energy demand from other sources (coal, gas, nuclear, oil) decreased. Report [**11**] also shows a reduction by 6.6% in carbon dioxide emissions for the year 2020, with respect to 2019. Since the use of heating and cooling systems powered by electricity is growing, an estimation on an hourly basis of CO_2 emissions is important in order to enhance the operation of these systems when the grid is mainly powered by RES. In the last years, the use of detailed software to perform dynamic simulations of buildings played a very crucial role in choosing and optimizing the most appropriate typology of generation and emission systems. In the recent literature, several studies deal with this topic [**12-14**]; other works evaluate the carbon dioxide emission factor for power generation by fossil and renewable energy sources [**15-18**]. As the authors are concerned, there is a lack of studies that calculate dynamically the CO_2 emissions and introduce an explicitly interpolating function, when, for example, an electric heating system, such as a heat pump, is powered by the electric grid. Major part of the models found in the literature, used to determine hourly emission factors, are referred to the electricity produced in a single country, neglecting the electricity exchanges with other countries. Noussan et al. [**15**] determine the hourly emission factors considering the total energy produced in Italy, for 6 years (2012-2017). Marrasso et al. in [**16**] determine the hourly emission factors (for years 2016 and 2017), considering the electric energy produced in Italy and neglecting the energy exchanges with foreign countries to which the Italian power grid is connected to. They also affirm that the use of constant value for energy and environmental indicators has a negative impact of the choice of electricity versus fossil fuel-based technologies. In [**17**], Neirotti et al. compare the emissions of residential and commercial heat pumps considering an annual average emission factor and an hourly emission factor, for different countries in Europe. The hourly emission factor is referred to the energy production of the single analyzed country, and the paper shows that the difference in terms of total emissions considering the hourly and the annual mean emission factor increases together with the share of renewables. Clauß et al. [**18**] propose a model for the estimation of carbon dioxide emission factor in Norway, determining different hourly emission factors for each of the 6 zones in which the Norwegian power grid is subdivided. The authors take into account the electric energy produced in every single zone, and the electricity exchanges with foreign countries. Results indicate that the emission factor varies significantly during the day. The authors stress the importance of emission reduction, and the use of predictive controls for building energy management. Hamels [**19**] focused on the importance of calculating CO_2

emission and primary energy factors to correctly evaluate all the electric-powered systems, mainly transport and heating services, connected to the grid. In the study is also mentioned the significance of contemplate imports from other countries.

In the present study, a new method, based on the development of a periodic function, to determine the hourly carbon dioxide emission factors for a device connected to the Italian power grid is presented. The described method considers the electricity exchanges with foreign countries and calculates the CO_2 emissions considering the electric energy demand, not only the one produced in Italy. In the study two models, one called “detailed model” and another called “simplified model” are presented and compared. In the detailed model the CO_2 emission factors are calculated based on the raw collected data during the 4 years 2016-2019, whilst the simplified model defines an hourly averaged simplified function from the abovementioned data over the four years considered, that approximates the carbon dioxide emissions. The so-called “simplified model”, although it results less accurate than the “detailed model”, can be easily implemented in dynamic simulation software because it is expressed by a periodic function characterized by – only- eight coefficients. The suggested function is particularly useful in all the energy evaluations for dynamically calculating the CO_2 emissions when a common electric device is connected to the grid. Regarding building energy performance simulations, the suggested function is a valid tool for determining the carbon dioxide emissions in the atmosphere of a grid-connected electric heat pump; moreover, with the proposed tool, users can study different utilization strategies not only to reduce the energy consumption, but also the CO_2 emissions.

2. Materials and Methods

To establish the carbon dioxide emission factor for the Italian power grid on hourly basis, we propose and compare two models as sketched in **Figure 1(a)**, where EE stands for electric energy, in kWh. The models calculate the hourly carbon dioxide emission factor with reference to the energy taken from the power grid and considering not only the net production of the specific hour in Italy, but also the energy imported and exported every hour. The hourly emission factor EF (kg/kWh) is defined as the quantity of carbon dioxide produced m_{CO2} (kg) for every kWh of electrical energy obtained from the Italian power grid EE (kWh), i.e.

$$EF = \frac{m_{CO2}}{EE} \tag{1}$$

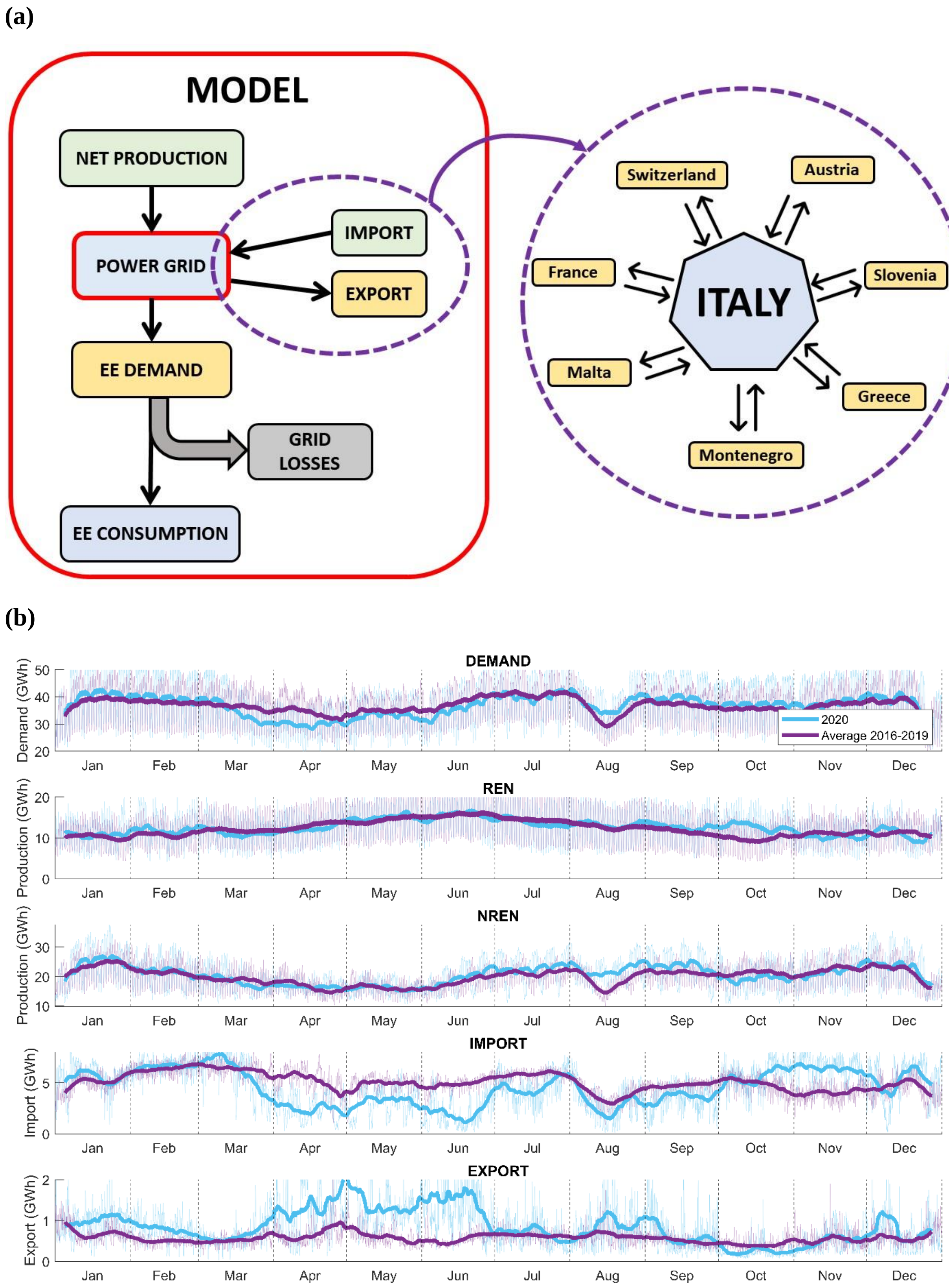

Figure 1. Scheme of the model for estimation of hourly emission factor and focus on imported and exported electricity (a); trends of electricity demand for Italy, internal production (subdivided into renewable (REN) and non-renewable (NREN)), total import and export (b). The trends in figure 1(b) are related to the year 2020 and the hourly

average for the four years from 2016 to 2019; the bold line shown here refers to a moving average throughout 200 h, while the fine lines refer to hourly values.

All the electric power grids in Europe are interconnected; therefore, the electrical energy taken in a specific hour from a device connected to the power grid in one country, could be produced in other country in Europe. In this scenario, the electric energy produced in Italy for example, has a direct impact on emission of another country, which is always characterized by a different carbon emission factor due to the different power production mix of the electric energy respect to Italian electricity production mix. The models evaluate the quantity of hourly energy imported and exported by Italy versus other European countries to which the power grid has physical connections, as shown in **Figure 1(a)**.

2.1. Energy production and emission factors data

The proposed models require two sets of data:

- Electricity production in Italy and electricity exchanges with the other countries;
- Carbon dioxide emission factors for Italy (categorized by different sources) and annual emission factors for the other Countries that have energy exchanges with Italy.

Energy production and exchanges data are obtained from the Italian Transmission System Operator Terna. In detail, hourly data of the energy production for 5 years, from 2016 to 2020, are collected [**20**] and categorized in geothermal, hydroelectric, photovoltaic, biomass, wind source, thermal (non-renewable) and self-consumption. Data related to hourly energy exchange with foreign countries are also collected from the same online platform and for the same four years (2016-2020): in this case, for every hour the amount of energy imported or exported for the Countries shown in **Figure 1(a)** (Austria, France, Switzerland, Greece, Slovenia, Malta and Montenegro) are downloaded. Data related to the electricity exchange with Montenegro are not taken into account, mainly because the exchange of electricity between Montenegro and Italy started, as shown in Terna platform, only from 27 December 2019. According to the authors' opinion, the overall quality of data is good for each considered year.

In **Figure 1(b)** the data of renewable production, non-renewable production, import, export and demand of electric energy related to Italian power grid are presented, downloaded from [**20**], from years 2016 to 2020. Focusing on renewable production on yearly basis, for all the five years considered, the maximum production occurs during summer, in June and July, while a minimum of the production arises in autumn and winter months. With reference to non-renewable, the minimum values of production can be observed in April and May. Reductions in imported electricity can be noticed during August, thus associated to summer holidays and the consequent decrease in production of Italian factories. Notably, the import of electricity is larger than export for all the 5 years considered. Considering year 2020, which is the year of the outbreak of Covid-19 pandemic (**Figure 1(b)**), we can observe that during the months characterized by lockdown and/or reduction of factories activities (namely part of March, April, May and first two weeks of June), there was a slight decrease of electricity demand respect to other four years. During the same period, there was no difference in energy production from renewable and non-renewable sources can be observed. Thus, the major difference in comparison with the previous four years is related to the electricity imported and exported from the country: during 2020 lockdown and restrictions in Italy there was an increase in export to foreign countries and an important decrease in electric energy imported from foreign countries, as illustrated by data from Terna platform [**20**] (export +49.2%, import -27.4% and electricity demand +0.4%, for year 2020 respect to annual average of years 2016-2019).

Considering the electric energy production from different renewable sources [**20**], the largest share comes from hydropower and photovoltaic, while the electricity from geothermal source is minimal. Moreover, the maximum production from photovoltaic is for both 2016 and 2019 in June and July, that are months characterized by the highest solar irradiance and sunshine duration. If we consider hydropower production, the maximum production occurs in June, on the contrary, energy production from biofuels and from geothermal source is relatively constant during all the year. Finally, data collected from [**20**] show that electricity production from wind is the most variable source among all renewable sources considered; wind production also displays minimum values during summer months.

Now, if we focus on renewable production considering small time frames (**Figure 2**) we can observe that hydropower (and partly biofuels) generation have a trend like the common daily trend of electric energy demand in Italy, with two peaks of demand, the first one during morning and the latter one on evening. This aspect is due to the programmability of the two sources aforementioned, in particular for hydropower generation this is possible by means of pumped storages that allow to produce electricity in correspondence of the two daily peaks of electric energy demand. Conversely, the other two sources reported in **Figure 2**, wind and photovoltaic, are non-programmable: wind source shows a very irregular trend, while photovoltaic displays a regular daily trend, with maximum generation at midday. A further aspect that can be noticed is the frequency of the generation from photovoltaic, biofuels and hydropower: they have a periodicity of 24 hours.

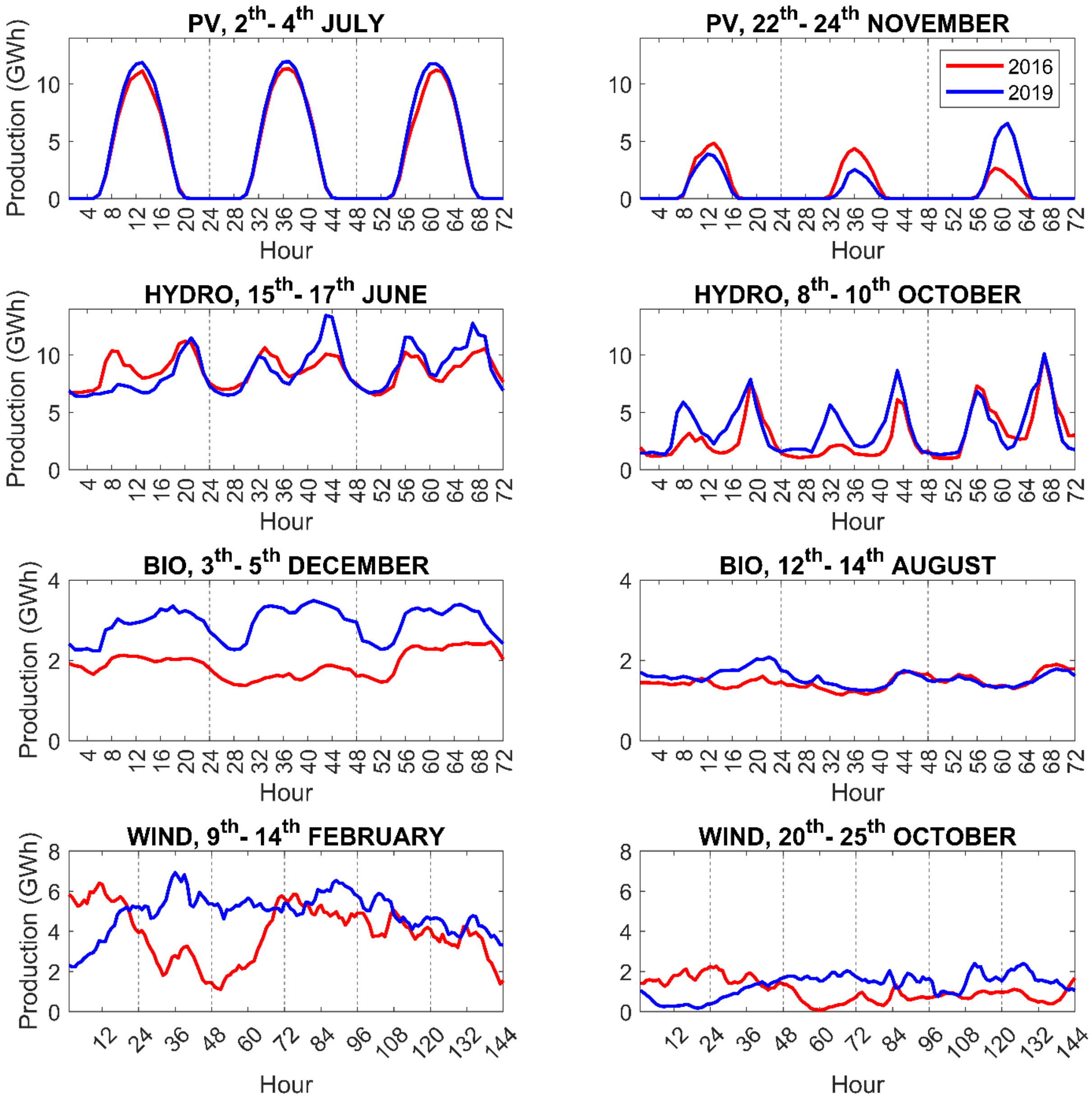

Figure 2. Focus on the trend of renewable production for different days of the year.

The annual emission factors for non-renewable production for Italy considered in this paper are taken from the ISPRA (Italian Institute for Environmental Protection and Research) annual report [**21**] for 4 years (2016-2019), together with the annual emission factors for foreign Countries connected to Italian power grid, taken from annual AIB (Association of Issuing Bodies) report [**22**]. No information is available regarding the source of electricity imported (namely categorization on renewable, non-renewable…), and, therefore, a yearly mean emission factor given by [**22**] has been used for electricity imported from other Countries. However, the decision to consider in the model the electricity imported for the determination of carbon dioxide intensities, even if has been considered an annual constant emission factor value for the imported electricity, is due to the consideration that an important part of electric energy consumed in Italy comes from other Countries. It can also be noticed that the majority of the works about this topic in literature, as reported by Hamels [**19**], don’t take into account the “net foreign exchange”, resulting in a overestimation (or underestimation) of the carbon dioxide intensities, especially for countries characterized by an important part of electricity imported. The emission factors for renewable sources are taken from [**23**] (values expressed in kg/kWh are respectively 0.230 for bio-energies, 0.038 for geothermal, 0.024 for hydroelectric, 0.045 for photovoltaic and 0.011 for wind production). Unfortunately, the values of the emission factor related to year 2020 are not yet available for Italian non-renewable production, according to ISPRA, therefore the analysis in the present paper will focus only on years from 2016 to 2019.

2.2 Model to determine the hourly emission factor

As explained in section 2, the detailed model considers the carbon dioxide emission factors for a device connected to the Italian power grid, referred to the electric energy taken from power grid. To determine the hourly emission factor EF_h (kg/kWh), the following quantities are introduced. First, let us define the mass of carbon dioxide hourly produced by non-renewable electricity production in Italy $m_{nren,h}$ (kg), from renewable electricity production in Italy $m_{ren,h}$ (kg) and from electricity imported from abroad $m_{imp,h}$ (kg):

$$m_{nren,h} = EE_{nren,h} \cdot EF_{nren} \tag{2}$$

$$m_{ren,h} = \sum_j EE_{ren,j,h} \cdot EF_j \tag{3}$$

$$m_{imp,h} = \sum_k EE_{imp,k,h} \cdot EF_k \tag{4}$$

The hourly carbon dioxide production due to internal electricity generation in Italy is the sum of hourly renewable and non-renewable and import from foreign Countries, and is expressed by $m_{int+imp,h}$ (kg):

$$m_{int+imp,h} = m_{imp,h} + m_{ren,h} + m_{nren,h}, \tag{5}$$

The sum of hourly electric energy production in Italy and hourly import from abroad, namely $EE_{int+imp,h}$ (kWh), can be expressed as

$$EE_{int+imp,h} = \sum_k EE_{imp,k,h} + \sum_j EE_{ren,j,h} + EE_{nren,h} \tag{6}$$

Where $EE_{imp,k,h}$ (kWh) refers to the hourly electricity imported for the k-th country (reported in **Figure 1**). On account of eqs. (5-6), the hourly mass of carbon dioxide $m_{exp,h}$ (kg) related to hourly electricity exported $EE_{exp,h}$ (kWh), can also be expressed as

$$m_{exp,h} = m_{int+imp,h} \cdot \frac{EE_{exp,h}}{EE_{int+imp,h}} \tag{7}$$

Other useful quantities to determine the expression of the hourly emission factor are the hourly total mass of carbon dioxide emission $m_{tot,h}$ (kg), given by the sum of CO_2 coming from internal production in Italy and import and subtracting the hourly CO_2 related to electricity exported in other Countries,

$$m_{tot,h} = m_{nren,h} + m_{ren,h} + m_{imp,h} - m_{exp,h}, \tag{8}$$

and the hourly electricity demand for Italy $EE_{tot,h}$ (kWh),

$$EE_{tot,h} = EE_{nren,h} + EE_{ren,h} + EE_{imp,h} - EE_{exp,h}. \tag{9}$$

It may be observed that the mass of carbon dioxide related to electric energy exported to other Countries is subtracted (as the electric energy exported to other Countries) because the model has the aim to determine an hourly emission factor related to electric energy taken from a disposal connected to the Italian power grid, and not to the total electricity that flows every hour on the Italian power grid but is consumed in other Countries.

Let us now introduce the coefficient of grid losses for Italian power grid p (for years 2016-2019, [**24**]), in order to determine the final expression of hourly emission factor EF_h,

$$EF_h = \frac{m_{tot,h}}{EE_{tot,h}} p, \tag{10}$$

or, equivalently,

$$EF_h = \frac{EE_{nren,h} \cdot EF_{nren} + \sum_j EE_{ren,j,h} \cdot EF_j + \sum_k EE_{imp,k,h} \cdot EF_k - m_{int+imp,h} \cdot \frac{EE_{exp,h}}{EE_{int+imp,h}}}{\sum_k EE_{imp,k,h} + \sum_j EE_{ren,j,h} + EE_{nren,h} - EE_{exp,h}} p. \tag{11}$$

The use of coefficient p allows one to refer the emission factor to the electricity taken from a device connected to the Italian power grid instead of to the total hourly electric energy provided by the grid.

The “detailed” model presented in this section is employed to determine the emission factors EF_h for 4 years (2016-2019), considering the data specified in section 2.1. The hourly emission factor obtained varies periodically and its value is smaller during months characterized by a large share of renewable.

2.2. Approximation of the model by means of a periodic function

A time-dependent function was defined to express the hourly emission factor previously given; the detailed model in fact provides the values of EF_h for all the hours of the year considered, but an approximated periodic function (“simplified model”) defined by some coefficients facilitates the analysis and the use of the hourly emissions of a device connected to the electric grid and allows one to introduce predictable behaviors.

As mentioned before, the hourly emission factor varies during the year and has also periodic fluctuations characterized by a period of 24 hours. A function that approximates EF_h trend is a sine envelope function, defined as:

$$ef(t) = f(t)\Omega(t) + \big(1 - \Omega(t)\big)g(t) \tag{12}$$

where $ef(t)$ is the approximated hourly time-dependent emission factor, $f(t)$ and $g(t)$ are two polynomial functions and $\Omega(t)$ is a periodic function. The expressions of functions $f(t)$, $g(t)$ and $h(t)$ are given by

$$\Omega(t) = \sin^2(\omega t + \delta) \tag{13}$$

$$f(t) = a_1 t^2 + b_1 t + c_1 \tag{14}$$

$$g(t) = a_2 t^2 + b_2 t + c_2, \tag{15}$$

where ω, δ, a_1, b_1, c_1, a_2, b_2, c_2 are coefficients determined in order to minimize the error of the approximated formula respect to the EF_h value given by the model.

The sinusoidal function (12) has been chosen in order to obtain a periodic function with a period of 24 hours, since in general the periodicity of the emission factor is 24 hours, according to the "detailed" model; the emission factor trend well reproduces the daily electricity production curve in Italy. The two functions $f\,(t)$ and $g\,(t)$ are the approximate maximum and minimum value that the emission factor can reach, in fact they are precisely the ones that determine the amplitude of the final function that gives rise to the "simplified" model.

The values of the coefficients are reported in **Table 1** for the considered years. The coefficients for a function given by the mean values of the hourly EF_h, for the years 2016-2019 are determined and reported in **Table 1** as well.

Table 1. Coefficients for the approximated periodic function.

Coefficient	2016	2017	2018	2019	Average
a_1	3.83E-09	3.36E-09	1.75E-09	4.01E-10	2.08E-09
b_1	-2.4E-05	-2.7E-05	-1.1E-05	-6.3E-06	-1.5E-05
c_1	0.38544	0.39784	0.34238	0.34044	0.35575
a_2	5.35E-09	5E-09	2.18E-09	1.55E-09	3.85E-09
b_2	-3.9E-05	-4.3E-05	-1.7E-05	-1.5E-05	-3.1E-05
c_2	0.32248	0.33941	0.2985	0.27489	0.3175
ω	0.1309	0.1309	0.1309	0.1309	0.1309
δ	1.51	1.53	1.5	1.52	1.51

In the present study the reported coefficients are determined with reference to the Italian power grid; however, whenever data are available the method could be applied to any other Country.

Despite the limited of amount of data available, **Table 1** shows a temporal trend for the coefficients reported, excluding year 2017. For example, we can observe a decrease of coefficients a_1, a_2, c_1 and c_2, and an increase of b_1 and b_2 over the years. We underline that the decrease of the coefficients c_1 and c_2, evident if year 2017 is neglected, means that average annual emissions are reducing respect to time.

In **Figure 3** the EF_h values of the detailed model and of the simplified model are compared. The figure refers only to year 2019. Moreover, in **Figure 4** the hourly emission factor from the two models is reported, for years 2016-2019, for some specific (working) days, allowing a more evident comparison between real data and the interpolating function. The mean absolute error (MAE, eq. 16) and the root mean squared error (RMSE, eq. 17) ranges in 0.029-0.031 and 0.035-0.038 respectively, for the four years, referring to the simplified model with respect to the detailed model:

$$MAE = \frac{\sum_{h=1}^{8760} |EF_h - ef_h|}{8760} \tag{16}$$

$$RMSE = \sqrt{\frac{\sum_{h=1}^{8760} (EF_h - ef_h)^2}{8760}} \tag{17}$$

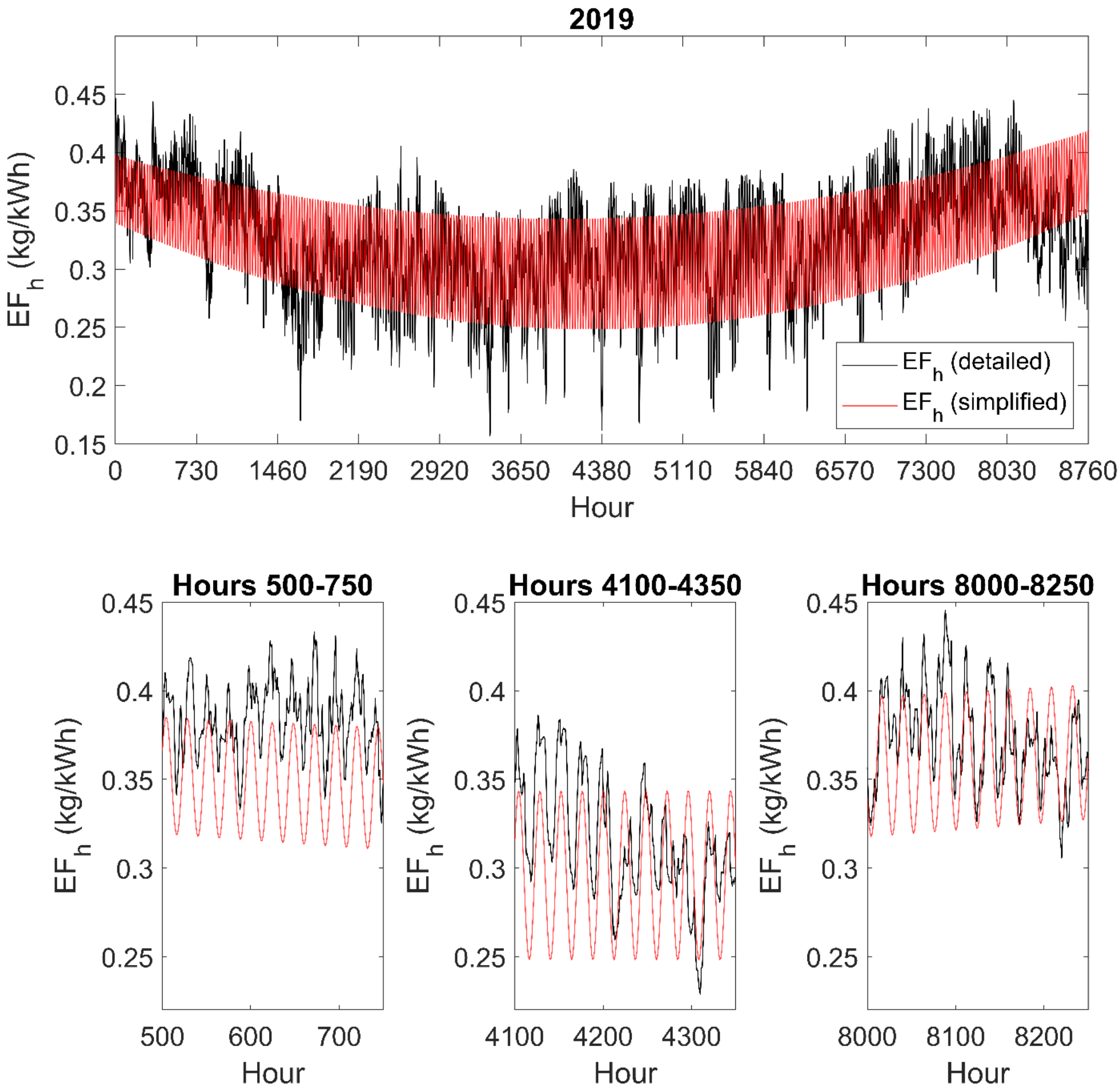

Figure 3. Hourly emission factor from the detailed model and from the simplified model for year 2019.

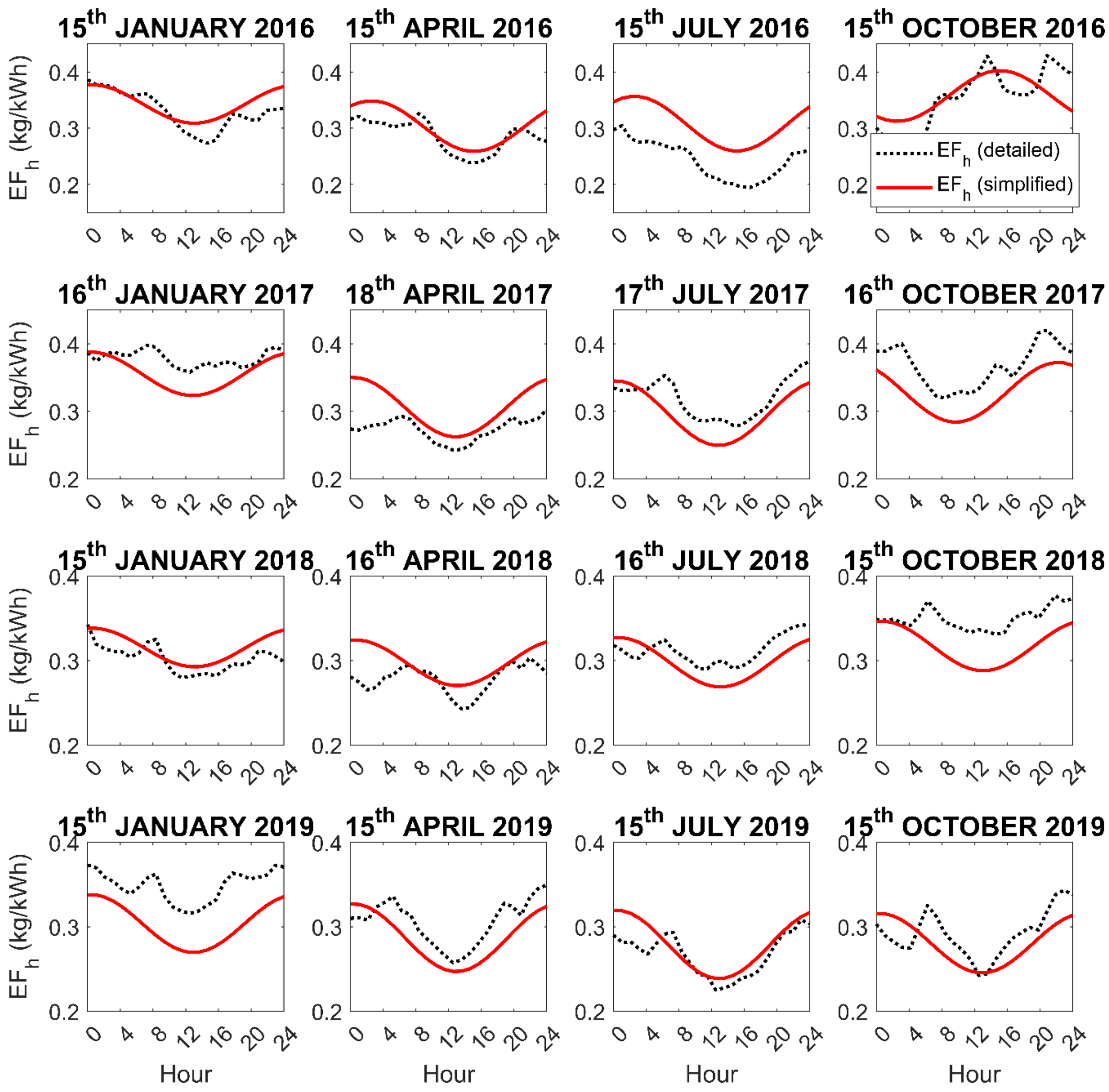

Figure 4. Hourly emission factor from the detailed model (black dotted line) and from the simplified model (red line) for some working days (years 2016-2019).

3. The case study

In this section the authors analyze the results, in terms of carbon dioxide emissions, of a case study in which an air-to-water heat pump connected to Italian power grid is employed as a generation system, for a residential building placed in Milan. The building under investigation is the one proposed by IEA [**25**], in particular the two-floor family house characterized by a space heating demand of 45 kWh/(m^2y).

The total floor area of the building considered in the simulations is 360 m^2 and the main building envelope components (floor, roof, internal and external walls) are characterized by a transmittance ranging between 0.241 W/m^2K and 0.885 W/m^2K.

An air change rate due to infiltration of 0.3 h^{-1} for all the thermal zones is assumed, and all windows are double pane characterized by a 4-16-4 mm construction, filled with Argon gas. The frame is 15% of the total area of the window (total area of the glass and frame), and the overall transmittance of the window can be estimated as U-window = 1.5 W/m^2K. Thermal gains due to inhabitants and to electric equipment are considered variable during the day, as proposed in [**26**]. More in detail, the thermal gain caused by a single inhabitant is divided in two parts: 20 W due to convection, and 40 W due to radiation [**25**]; the thermal gains due to electrical equipment are attributed half to convection and half to radiation as well. For any parameter here not explicitly mentioned for sake of brevity, the value proposed by IEA Task 44 [**25**] for SFH45 are employed. In the present paper, the software package TRNSYS is used to model the building, and in particular, the multizone building TRNSYS type 56 [**27, 28**].

4. Results and discussion

In **Figure 5** the electric energy demand for heating and cooling season is reported. The total energy demand of the reversible air-to-water heat pump is 5079 kWh for heating season and 4150 kWh for cooling season. [**26**].

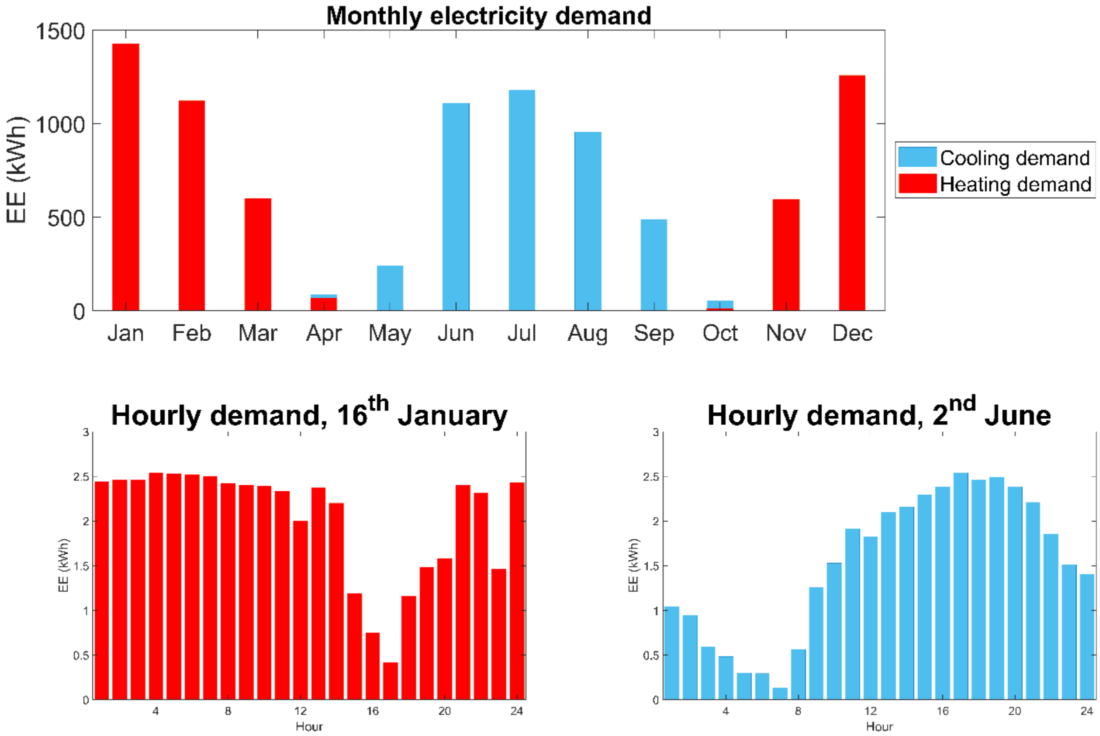

Figure 5. Monthly electricity demand (kWh) by the residential heat pump during heating and cooling season (top figure), and hourly heating and cooling demand for two representative days of the heating and cooling season respectively (bottom left and right).

4.1. Total carbon dioxide emissions and carbon dioxide emission factors

The total emissions for heating and cooling are reported in **Table 2**, considering the detailed model previously introduced, and using the approximated periodic function (simplified model). Results refer to the years 2016-2019 and report an averaged value as well (denoted by subscript *m*), both of the hourly emission factor $EF_{h,m}$ on the four years considered, defined as

$$EF_{h,m} = \sum_{n} EF_{h,n}\,, \tag{18}$$

where n denotes the *n-th* year (2016-2019), and also of the approximated mean function $ef_m(t)$, determined according to the procedure reported in section 2.3, and expressed by the coefficients reported in **Table 1**, column “Average”.

Seasonal carbon dioxide emissions $\dot{m}_n$ (kg) in **Table 2** have been determined multiplying the hourly emission factor obtained from the detailed and simplified model by the hourly electricity demand EE_h (kWh) of the heat pump, as shown in eqs. (19)-(20):

$$\dot{m}_{n,detailed} = \sum_h EF_{h,n} \cdot EE_h \tag{19}$$

$$\dot{m}_{n,simplified} = \sum_h ef_n(h) \cdot EE_h \ . \tag{20}$$

Table 2. Annual emissions (kg) and percent error (%) for heating and cooling, resulting from the model to estimate EF_h (detailed model), from the approximated function (simplified model, considering the hourly mean averaged over 4 years, 2016-2019) and a constant emission factor (yearly average of the EF_h obtained by the detailed model).

	Year	**Detailed model**	**Simplified model**	**Constant emission factor**	**Error (%) simplified model vs. detailed model**	**Error (%) constant emission factor vs. detailed model**
Annual emissions (kg) for heating	**2016**	1832	1842	1699	0.55	7.27
	2017	1780	1798	1639	0.98	7.94
	2018	1628	1643	1564	0.87	3.96
	2019	1487	1514	1454	1.81	2.21
	Averaged	1682	1689	1589	0.42	5.53
Annual emissions (kg) for cooling	**2016**	1232	1241	1388	0.73	12.71
	2017	1213	1196	1339	1.41	10.41
	2018	1222	1210	1278	0.94	4.58
	2019	1122	1116	1188	0.51	5.92
	Averaged	1197	1190	1298	0.58	8.46

Table 2 shows that the approximated function gives results very similar to the results obtained by the detailed model, while the results coming from the use of a constant emission factor present higher differences respect to the one obtained by the detailed model.

The detailed model gives the most accurate information on carbon dioxide emissions. **Table 2** shows that the evaluations coming from the approximated model, and even more from the assumption of a constant emission factor, underestimate the annual emissions for heating while overestimate the annual emissions for cooling. This is due both to the fact that any approximation mathematically cannot give the same precision of detailed data, and to the fact that in winter season the overall contribution of the renewable sources is smaller than in summer. Now if we consider the average hourly values of the detailed model, given by eq. (16), and the average approximated periodic function, given by eqs. (12-15), we can compare the results in terms of percent error: the use of the approximated mean function implies a small percentage error (0.42% for heating and 0.58% for cooling). Therefore, we can assert that average approximated periodic function can be used for estimating the emissions accurately, obtaining result comparable to those obtained by the detailed model on yearly basis. On the contrary, the last column of **Table 2** shows that the constant emission factor induces a much less accurate estimation. In fact, in **Table 2** the percent error of the simplified model respect to the detailed model is reported for heating and cooling season, as well. We can observe that the function well approximates the carbon dioxide emissions for the case under investigation, with a maximum error of 1.8% for heating season and 1.4% for cooling. Therefore, it can be stated that yearly approximated functions well approximate the emissions given by the model.

In addition, for a comparison, the hourly emission factors for years 2016-2019 may be determined by neglecting the electricity imported and exported from foreign Countries (i.e., considering only Italian production, therefore using the emission factors for renewable and non-renewable production in Italy). In **Table 3** the values of the annual mean emission factor $\overline{EF_{n,int}}$ (kg/kWh) neglecting electricity exchanges with other Countries are reported for years 2016-2019 together with the percentage difference with respect to the annual mean emission factor $\overline{EF_n}$ (kg/kWh) obtained by the detailed model. The table shows that neglecting the electric energy exchanges with other Countries allows one to overestimate the annual emissions.

Table 3. Annual averaged emission factors (kg/kWh) and carbon dioxide annual emissions (kg) considering and neglecting electricity exchanges with other Countries, for heating and cooling season.

Year	**Season**	**Emissions (kg)**	**Difference in emissions (%)**	$\overline{EF_n}$	$\overline{EF_{n,int}}$ **(Only internal production)**	**Difference in annual emission factor (%)**
2016	Heating	2032	10.9	0.334	0.366	8.6
	Cooling	1325	7.6			
2017	Heating	1973	10.8	0.323	0.360	10.3
	Cooling	1333	9.9			
2018	Heating	1873	15	0.308	0.346	11.1
	Cooling	1341	9.7			
2019	Heating	1698	14.2	0.286	0.324	11.7
	Cooling	1243	10.8			

Lastly, the annual emission of carbon dioxide of the reversible air-to-water heat pump is determined by considering i) only internal electricity production and ii) electricity exchanges with other Countries. Results are reported in **Table 3**. It can be observed that the percentage difference between the two models is in the range 7.6-15%, with higher differences during the heating than during the cooling season.

5. Conclusions

In this study a new method to determine a function describing the hourly emissions of carbon dioxide of a device connected to power grid is presented and two models are introduced. In the determination of the coefficients of the proposed models, attention is paid to Italian data. The proposed models also evaluate the emissions due to the electricity exchange with foreign countries to which Italian power grid is connected. The hourly emission factors for carbon dioxide are determined with reference to a four year period (2016-2019).

An interpolating function for each year, as well as with reference to average conditions, is introduced, particularly useful in all the energy simulations for dynamically calculating the CO_2 emission when a common electric device is connected to the grid. The time-dependent function is a sine envelope function that contains three functions defined through coefficients. Based on the trends displayed by the 8 coefficients of the interpolating function, some behaviors are predicted. We underline that if year 2017 is neglected, the average annual emissions are reducing respect to time. The obtained results are applied to the special case of a residential heat pump installed in a building in Milan displaying a very good agreement, with a maximum error of 1.8% for heating season and 1.4% for cooling. Even lower values of the error are seen if the average approximating function is utilized. A comparison with the case of a constant emission factor is presented as well. Further investigations will suggest the evaluation of control strategies, in order to manage heat pumps utilization when the model suggest a GHG emissions reduction, mainly when the power grid requires less fossil fuels consumption. Moreover, when more years will be available the comparison may help evaluating if the actual transition to the renewable energies induces variations in the general trend of the coefficients.

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