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(Article begins on next page)

1 **Interpolating functions for CO₂ emission factors in dynamic simulations: the special case of a** 2 **heat pump**

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7 **Abstract**

8 The decarbonization strategy implies a strong reduction of greenhouse gas emissions in Europe.
9 The use of heat pumps as generation systems for space heating is increasing together with the
10 increase of renewable energy sources and is also increasing the attention paid to dynamic
11 simulations of heat pumps as well as greenhouse gas emissions. In the present study, a simplified
12 model to determine the hourly emissions of carbon dioxide of a device connected to the Italian
13 power grid is investigated, and an interpolating function for each year, as well as concerning
14 average conditions, is introduced, as a valid tool for deciding the utilization strategies of a heat
15 pump to reduce carbon dioxide emissions in the atmosphere, or, more in general, to evaluate the
16 CO₂ emissions when a common electric device is connected to the grid. The obtained results are
17 applied to the special case of a residential heat pump displaying a particularly good agreement,
18 with a maximum error of 1.8% for the heating season and 1.4% for the cooling one.

19

20 **Keywords:** dynamic CO₂ emissions; renewable energy sources; heat pumps; decarbonization.

21 **1. Introduction**

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

27 Space conditioning, heating and cooling play an important role in the whole energy demand in
28 Europe. Heat pumps, as generation systems for space climatization, are becoming increasingly
29 utilized in the European context [5]. The wide use of heat pumps, both air-source [6, 7] and
30 geothermal [8, 9], for heating and cooling, in addition to the electrification of transport and other
31 electric services, leads to the fastest growth of all the electricity sector. Moreover, electrification
32 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 CO₂ 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 CO₂ 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 CO₂

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

70 In the present study, a new method, based on the development of a periodic function, to determine
71 the hourly carbon dioxide emission factors for a device connected to the Italian power grid is
72 presented. The described method considers the electricity exchanges with foreign countries and
73 calculates the CO₂ emissions considering the electric energy demand, not only the one produced
74 in Italy. In the study two models, one called “detailed model” and another called “simplified
75 model” are presented and compared. In the detailed model the CO₂ emission factors are
76 calculated based on the raw collected data during the 4 years 2016-2019, whilst the simplified
77 model defines an hourly averaged simplified function from the abovementioned data over the
78 four years considered, that approximates the carbon dioxide emissions. The so-called “simplified
79 model”, although it results less accurate than the “detailed model”, can be easily implemented in
80 dynamic simulation software because it is expressed by a periodic function characterized by –
81 only- eight coefficients. The suggested function is particularly useful in all the energy evaluations
82 for dynamically calculating the CO₂ emissions when a common electric device is connected to
83 the grid. Regarding building energy performance simulations, the suggested function is a valid
84 tool for determining the carbon dioxide emissions in the atmosphere of a grid-connected electric
85 heat pump; moreover, with the proposed tool, users can study different utilization strategies not
86 only to reduce the energy consumption, but also the CO₂ emissions.

87 **2. Materials and Methods**

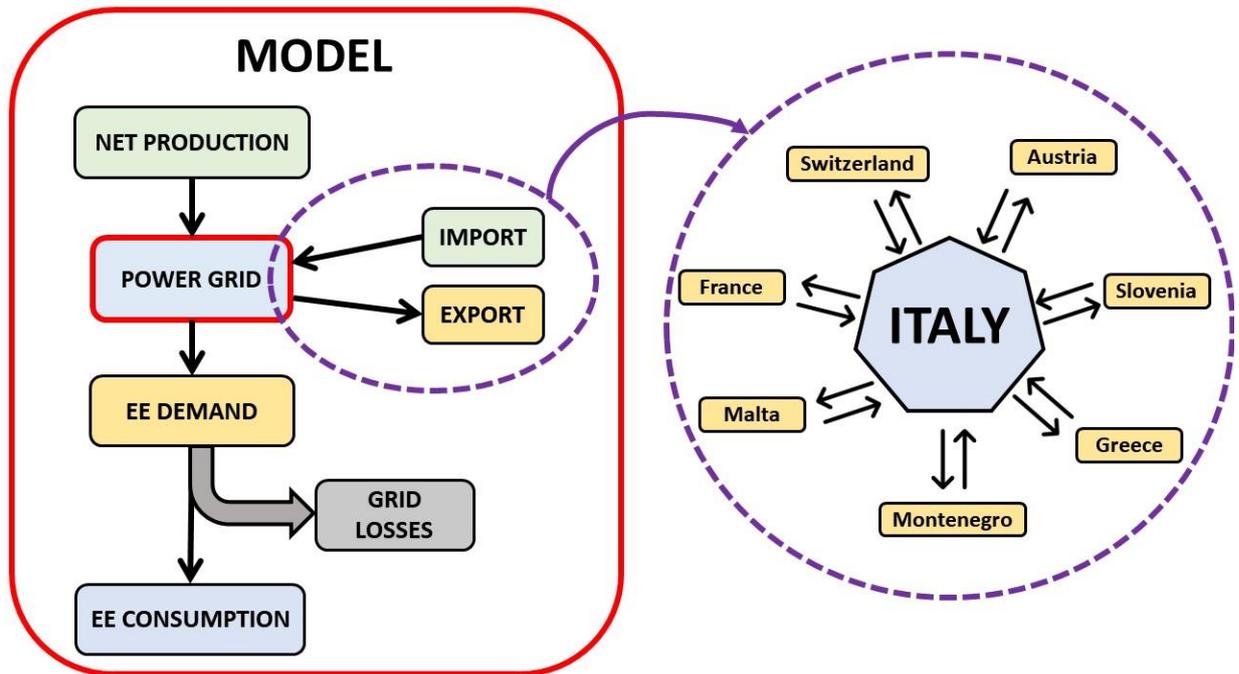
88 To establish the carbon dioxide emission factor for the Italian power grid on hourly basis, we
89 propose and compare two models as sketched in **Figure 1(a)**, where EE stands for electric energy,
90 in kWh. The models calculate the hourly carbon dioxide emission factor with reference to the
91 energy taken from the power grid and considering not only the net production of the specific hour
92 in Italy, but also the energy imported and exported every hour. The hourly emission factor EF
93 (kg/kWh) is defined as the quantity of carbon dioxide produced m_{CO_2} (kg) for every kWh of
94 electrical energy obtained from the Italian power grid EE (kWh), i.e.

$$EF = \frac{m_{CO_2}}{EE} \quad (1)$$

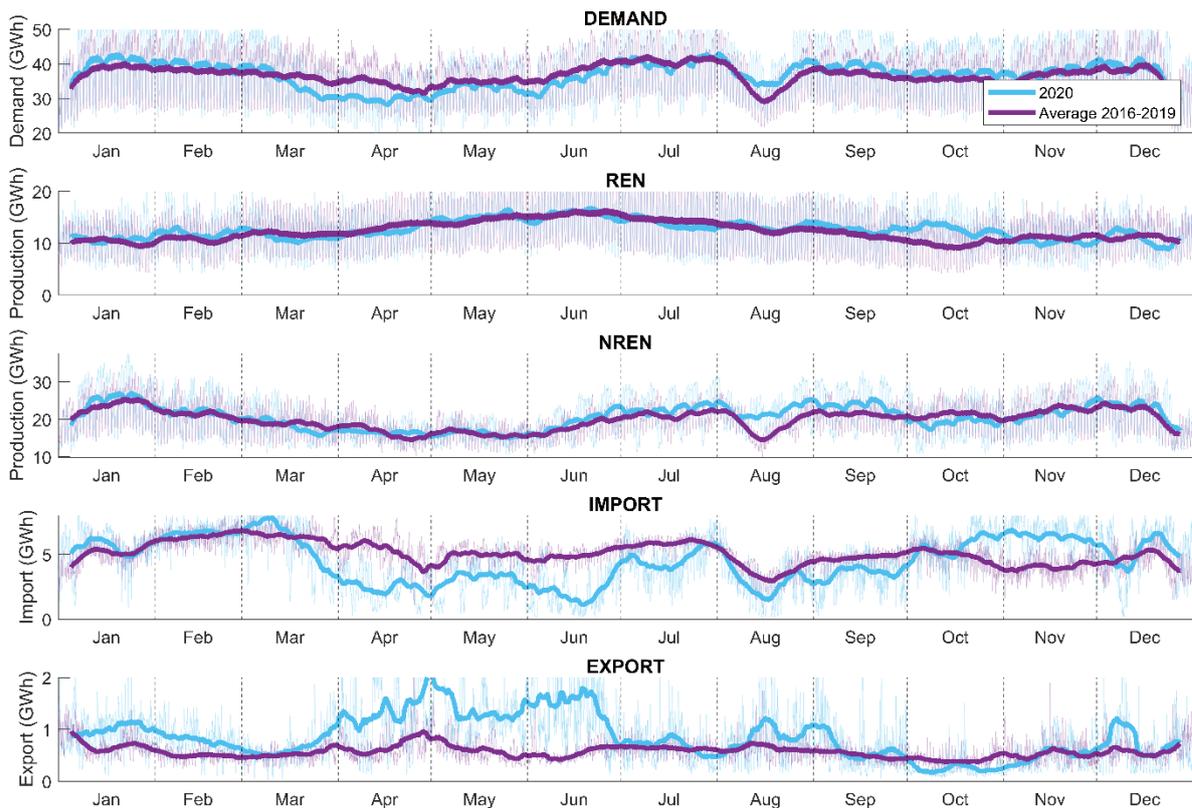
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96

(a)



(b)



97

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

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

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

111 **2.1. Energy production and emission factors data**

112 The proposed models require two sets of data:

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

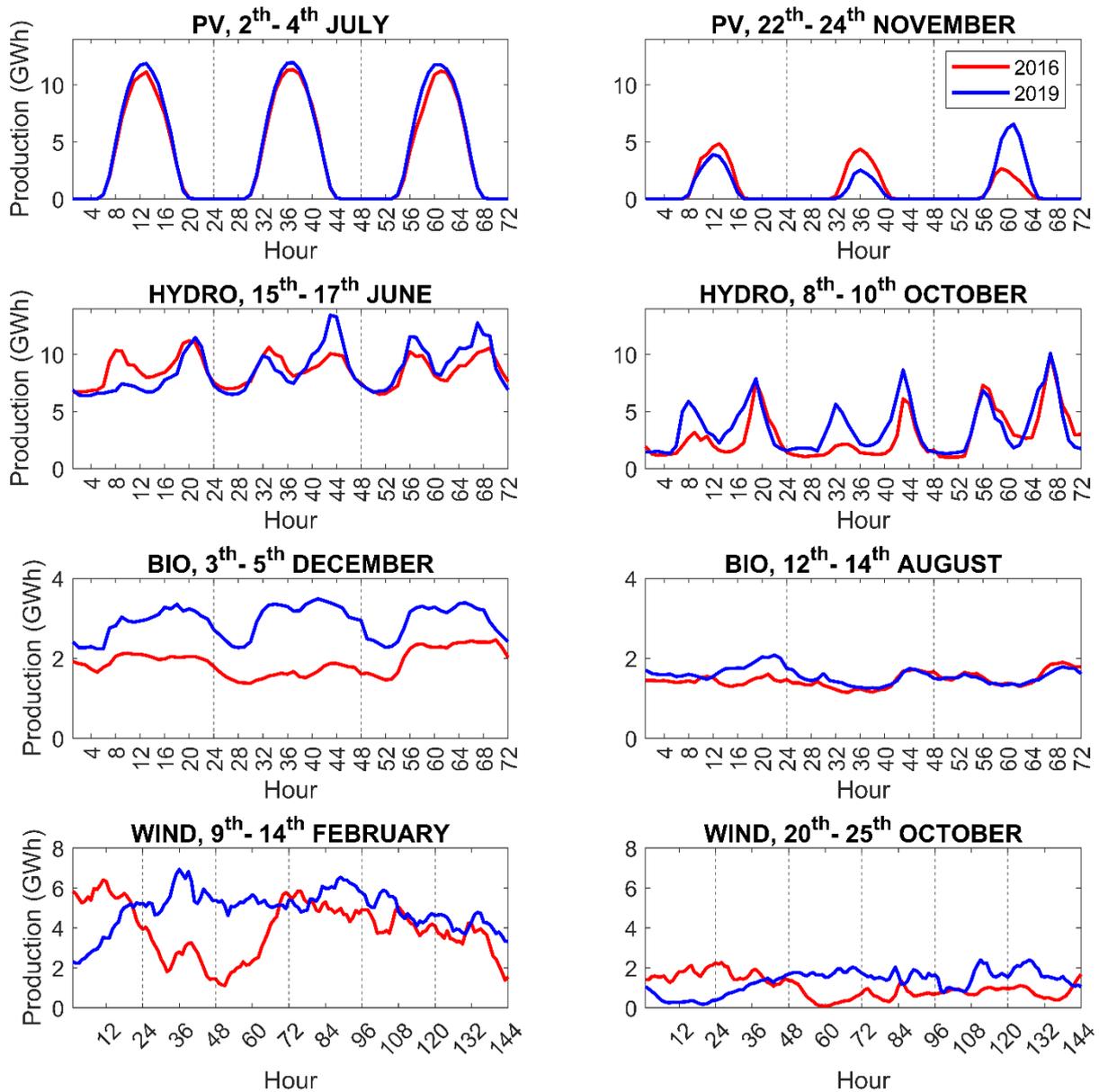
116 Energy production and exchanges data are obtained from the Italian Transmission System
117 Operator Terna. In detail, hourly data of the energy production for 5 years, from 2016 to 2020, are
118 collected [20] and categorized in geothermal, hydroelectric, photovoltaic, biomass, wind source,
119 thermal (non-renewable) and self-consumption. Data related to hourly energy exchange with
120 foreign countries are also collected from the same online platform and for the same four years
121 (2016-2020): in this case, for every hour the amount of energy imported or exported for the
122 Countries shown in **Figure 1(a)** (Austria, France, Switzerland, Greece, Slovenia, Malta and
123 Montenegro) are downloaded. Data related to the electricity exchange with Montenegro are not
124 taken into account, mainly because the exchange of electricity between Montenegro and Italy
125 started, as shown in Terna platform, only from 27 December 2019. According to the authors'
126 opinion, the overall quality of data is good for each considered year.

127 In **Figure 1(b)** the data of renewable production, non-renewable production, import, export and
128 demand of electric energy related to Italian power grid are presented, downloaded from [20], from
129 years 2016 to 2020. Focusing on renewable production on yearly basis, for all the five years
130 considered, the maximum production occurs during summer, in June and July, while a minimum
131 of the production arises in autumn and winter months. With reference to non-renewable, the
132 minimum values of production can be observed in April and May. Reductions in imported

133 electricity can be noticed during August, thus associated to summer holidays and the consequent
134 decrease in production of Italian factories. Notably, the import of electricity is larger than export
135 for all the 5 years considered. Considering year 2020, which is the year of the outbreak of Covid-
136 19 pandemic (**Figure 1(b)**), we can observe that during the months characterized by lockdown
137 and/or reduction of factories activities (namely part of March, April, May and first two weeks of
138 June), there was a slight decrease of electricity demand respect to other four years. During the
139 same period, there was no difference in energy production from renewable and non-renewable
140 sources can be observed. Thus, the major difference in comparison with the previous four years is
141 related to the electricity imported and exported from the country: during 2020 lockdown and
142 restrictions in Italy there was an increase in export to foreign countries and an important decrease
143 in electric energy imported from foreign countries, as illustrated by data from Terna platform [20]
144 (export +49.2%, import -27.4% and electricity demand +0.4%, for year 2020 respect to annual
145 average of years 2016-2019).

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

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



166

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

168 The annual emission factors for non-renewable production for Italy considered in this paper are
 169 taken from the ISPRA (Italian Institute for Environmental Protection and Research) annual report
 170 [21] for 4 years (2016-2019), together with the annual emission factors for foreign Countries
 171 connected to Italian power grid, taken from annual AIB (Association of Issuing Bodies) report
 172 [22]. No information is available regarding the source of electricity imported (namely
 173 categorization on renewable, non-renewable...), and, therefore, a yearly mean emission factor
 174 given by [22] has been used for electricity imported from other Countries. However, the decision
 175 to consider in the model the electricity imported for the determination of carbon dioxide intensities,
 176 even if has been considered an annual constant emission factor value for the imported electricity,
 177 is due to the consideration that an important part of electric energy consumed in Italy comes from

178 other Countries. It can also be noticed that the majority of the works about this topic in literature,
 179 as reported by Hamels [19], don't take into account the "net foreign exchange", resulting in a
 180 overestimation (or underestimation) of the carbon dioxide intensities, especially for countries
 181 characterized by an important part of electricity imported. The emission factors for renewable
 182 sources are taken from [23] (values expressed in kg/kWh are respectively 0.230 for bio-energies,
 183 0.038 for geothermal, 0.024 for hydroelectric, 0.045 for photovoltaic and 0.011 for wind
 184 production). Unfortunately, the values of the emission factor related to year 2020 are not yet
 185 available for Italian non-renewable production, according to ISPRA, therefore the analysis in the
 186 present paper will focus only on years from 2016 to 2019.

187 2.2 Model to determine the hourly emission factor

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

$$m_{nren,h} = EE_{nren,h} \cdot EF_{nren} \quad (2)$$

$$m_{ren,h} = \sum_j EE_{ren,j,h} \cdot EF_j \quad (3)$$

$$m_{imp,h} = \sum_k EE_{imp,k,h} \cdot EF_k \quad (4)$$

194 The hourly carbon dioxide production due to internal electricity generation in Italy is the sum of
 195 hourly renewable and non-renewable and import from foreign Countries, and is expressed by
 196 $m_{int+imp,h}$ (kg):

$$m_{int+imp,h} = m_{imp,h} + m_{ren,h} + m_{nren,h} \quad (5)$$

197 The sum of hourly electric energy production in Italy and hourly import from abroad, namely
 198 $EE_{int+imp,h}$ (kWh), can be expressed as

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

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

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

202 Other useful quantities to determine the expression of the hourly emission factor are the hourly
 203 total mass of carbon dioxide emission $m_{tot,h}$ (kg), given by the sum of CO₂ coming from internal
 204 production in Italy and import and subtracting the hourly CO₂ related to electricity exported in
 205 other Countries,

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

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

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

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

212 Let us now introduce the coefficient of grid losses for Italian power grid p (for years 2016-2019,
 213 [24]), in order to determine the final expression of hourly emission factor EF_h ,

$$EF_h = \frac{m_{tot,h}}{EE_{tot,h}} p, \quad (10)$$

214 or, equivalently,

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

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

218 The “detailed” model presented in this section is employed to determine the emission factors EF_h
 219 for 4 years (2016-2019), considering the data specified in section 2.1. The hourly emission factor

220 obtained varies periodically and its value is smaller during months characterized by a large share
221 of renewable.

222 **2.2. Approximation of the model by means of a periodic function**

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

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

$$ef(t) = f(t)\Omega(t) + (1 - \Omega(t))g(t) \quad (12)$$

231 where $ef(t)$ is the approximated hourly time-dependent emission factor, $f(t)$ and $g(t)$ are two
232 polynomial functions and $\Omega(t)$ is a periodic function. The expressions of functions $f(t)$, $g(t)$ and
233 $h(t)$ are given by

$$\Omega(t) = \sin^2(\omega t + \delta) \quad (13)$$

$$f(t) = a_1 t^2 + b_1 t + c_1 \quad (14)$$

$$g(t) = a_2 t^2 + b_2 t + c_2, \quad (15)$$

234 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
235 approximated formula respect to the EF_h value given by the model.

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

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

245

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

247

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

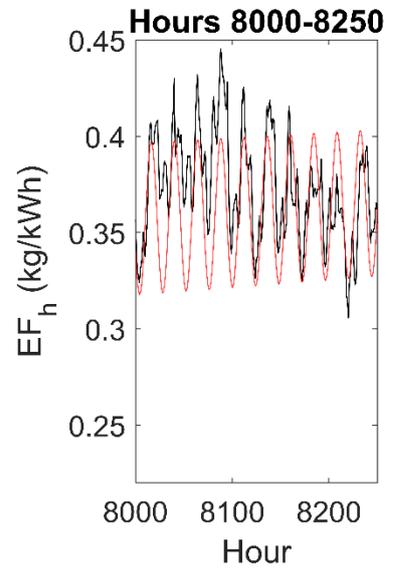
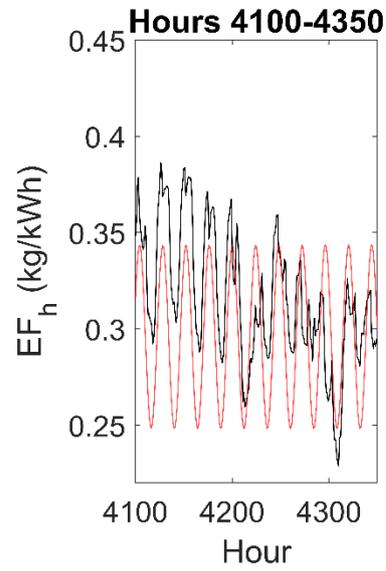
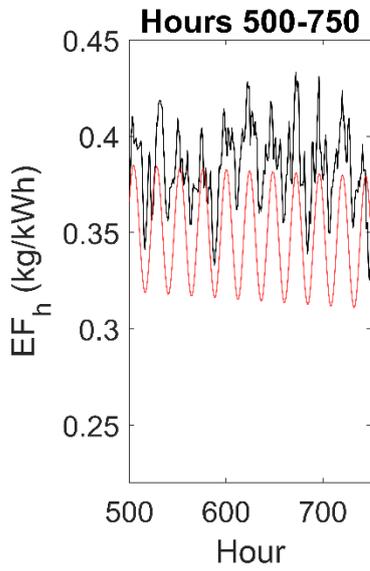
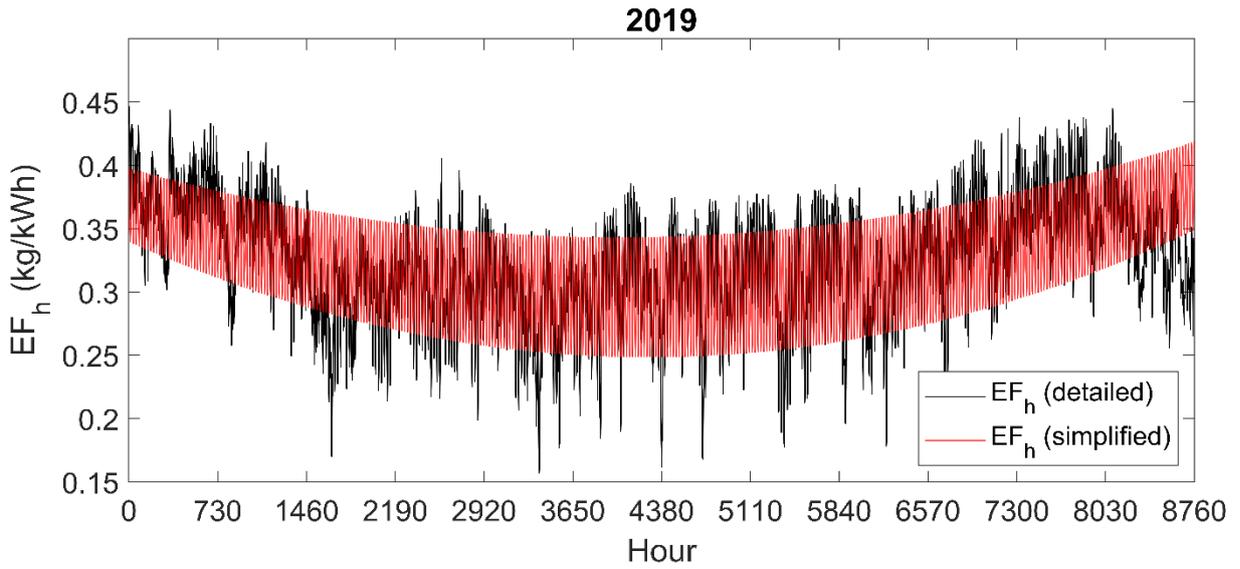
250 Despite the limited of amount of data available, **Table 1** shows a temporal trend for the
251 coefficients reported, excluding year 2017. For example, we can observe a decrease of
252 coefficients a_1 , a_2 , c_1 and c_2 , and an increase of b_1 and b_2 over the years. We underline that the
253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

255 In **Figure 3** the EF_h values of the detailed model and of the simplified model are compared. The
256 figure refers only to year 2019. Moreover, in **Figure 4** the hourly emission factor from the two
257 models is reported, for years 2016-2019, for some specific (working) days, allowing a more
258 evident comparison between real data and the interpolating function. The mean absolute error
259 (MAE, eq. 16) and the root mean squared error (RMSE, eq. 17) ranges in 0.029-0.031 and 0.035-
260 0.038 respectively, for the four years, referring to the simplified model with respect to the detailed
261 model:

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

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

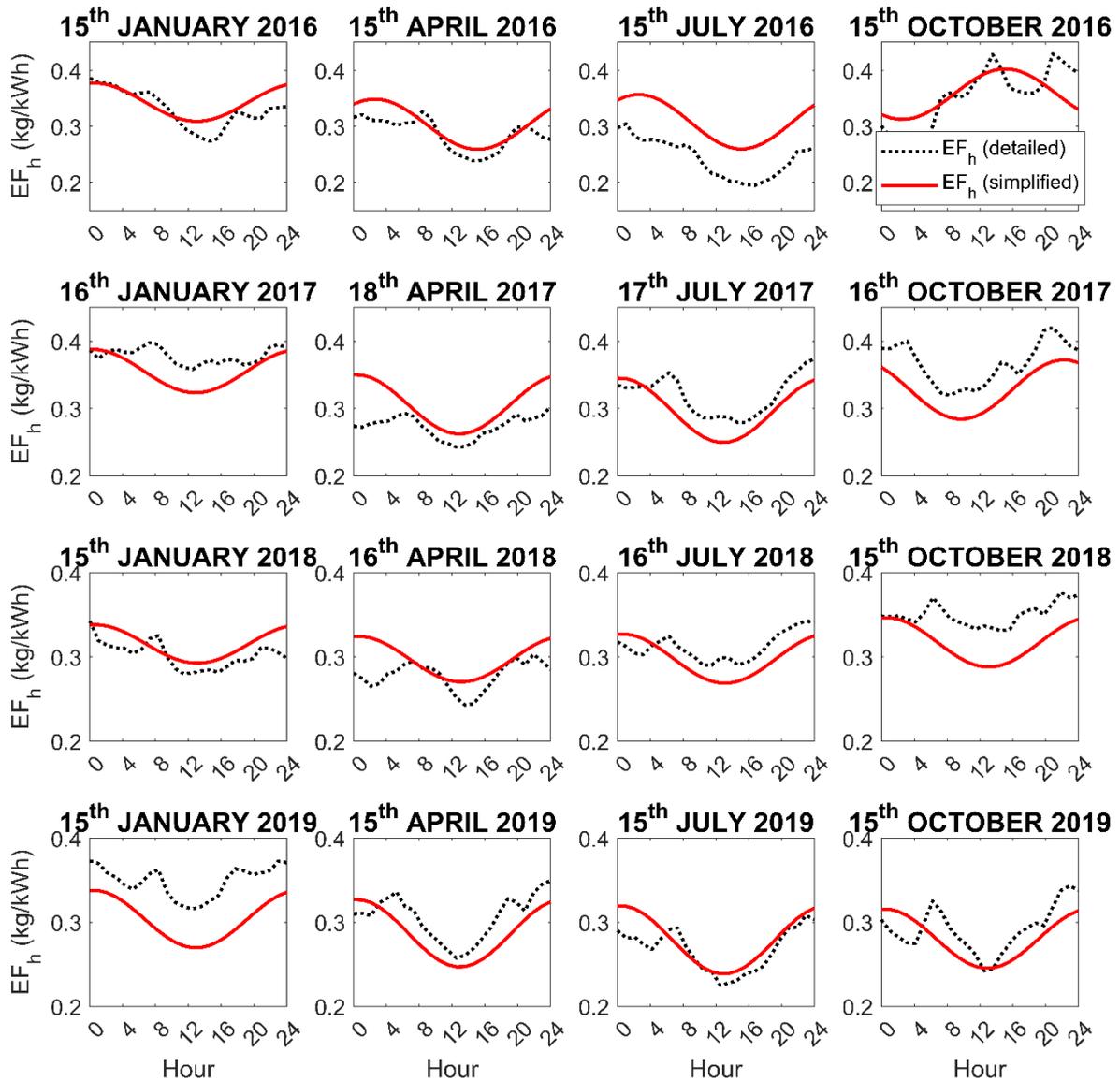
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263

264

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



265

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

268

269 **3. The case study**

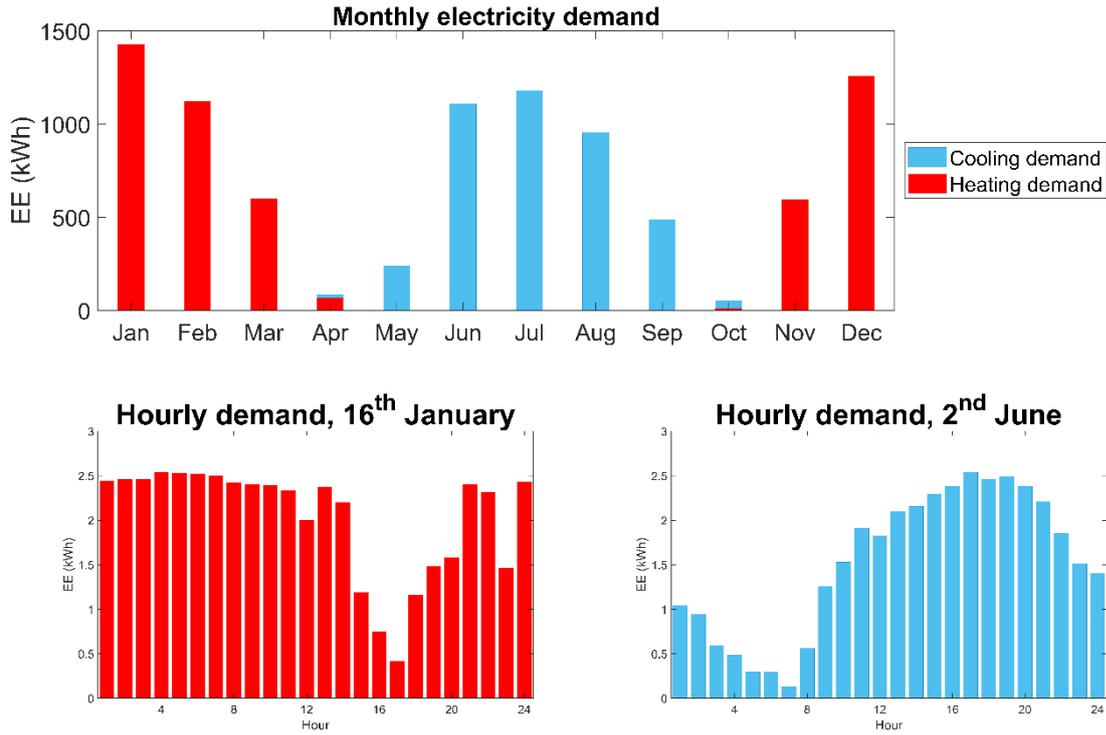
270 In this section the authors analyze the results, in terms of carbon dioxide emissions, of a case
 271 study in which an air-to-water heat pump connected to Italian power grid is employed as a
 272 generation system, for a residential building placed in Milan. The building under investigation is
 273 the one proposed by IEA [25], in particular the two-floor family house characterized by a space
 274 heating demand of 45 kWh/(m²y).

275 The total floor area of the building considered in the simulations is 360 m² and the main building
276 envelope components (floor, roof, internal and external walls) are characterized by a
277 transmittance ranging between 0.241 W/m²K and 0.885 W/m²K.

278 An air change rate due to infiltration of 0.3 h⁻¹ for all the thermal zones is assumed, and all
279 windows are double pane characterized by a 4-16-4 mm construction, filled with Argon gas. The
280 frame is 15% of the total area of the window (total area of the glass and frame), and the overall
281 transmittance of the window can be estimated as U-window = 1.5 W/m²K. Thermal gains due to
282 inhabitants and to electric equipment are considered variable during the day, as proposed in [26].
283 More in detail, the thermal gain caused by a single inhabitant is divided in two parts: 20 W due
284 to convection, and 40 W due to radiation [25]; the thermal gains due to electrical equipment are
285 attributed half to convection and half to radiation as well. For any parameter here not explicitly
286 mentioned for sake of brevity, the value proposed by IEA Task 44 [25] for SFH45 are employed.
287 In the present paper, the software package TRNSYS is used to model the building, and in
288 particular, the multizone building TRNSYS type 56 [27, 28].

289 **4. Results and discussion**

290 In **Figure 5** the electric energy demand for heating and cooling season is reported. The total
291 energy demand of the reversible air-to-water heat pump is 5079 kWh for heating season and
292 4150 kWh for cooling season. [26].



293

294

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).

295

296

297

4.1. Total carbon dioxide emissions and carbon dioxide emission factors

298

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

299

300

301

$$EF_{h,m} = \sum_n EF_{h,n}, \quad (18)$$

302

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”.

303

304

305

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):

306

307

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

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

308

309 **Table 2.** Annual emissions (kg) and percent error (%) for heating and cooling, resulting from the model to estimate
 310 EF_h (detailed model), from the approximated function (simplified model, considering the hourly mean averaged over
 311 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

312

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

316 The detailed model gives the most accurate information on carbon dioxide emissions. **Table 2**
 317 shows that the evaluations coming from the approximated model, and even more from the
 318 assumption of a constant emission factor, underestimate the annual emissions for heating while
 319 overestimate the annual emissions for cooling. This is due both to the fact that any approximation
 320 mathematically cannot give the same precision of detailed data, and to the fact that in winter
 321 season the overall contribution of the renewable sources is smaller than in summer. Now if we
 322 consider the average hourly values of the detailed model, given by eq. (16), and the average
 323 approximated periodic function, given by eqs. (12-15), we can compare the results in terms of
 324 percent error: the use of the approximated mean function implies a small percentage error (0.42%
 325 for heating and 0.58% for cooling). Therefore, we can assert that average approximated periodic
 326 function can be used for estimating the emissions accurately, obtaining result comparable to those
 327 obtained by the detailed model on yearly basis. On the contrary, the last column of **Table 2** shows

328 that the constant emission factor induces a much less accurate estimation. In fact, in **Table 2** the
 329 percent error of the simplified model respect to the detailed model is reported for heating and
 330 cooling season, as well. We can observe that the function well approximates the carbon dioxide
 331 emissions for the case under investigation, with a maximum error of 1.8% for heating season and
 332 1.4% for cooling. Therefore, it can be stated that yearly approximated functions well approximate
 333 the emissions given by the model.

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

342 **Table 3.** Annual averaged emission factors (kg/kWh) and carbon dioxide annual emissions (kg) considering and
 343 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			

344
 345 Lastly, the annual emission of carbon dioxide of the reversible air-to-water heat pump is
 346 determined by considering i) only internal electricity production and ii) electricity exchanges with
 347 other Countries. Results are reported in **Table 3**. It can be observed that the percentage difference
 348 between the two models is in the range 7.6-15%, with higher differences during the heating than
 349 during the cooling season.

350

351

352 5. Conclusions

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

359 An interpolating function for each year, as well as with reference to average conditions, is
360 introduced, particularly useful in all the energy simulations for dynamically calculating the CO₂
361 emission when a common electric device is connected to the grid. The time-dependent function
362 is a sine envelope function that contains three functions defined through coefficients. Based on
363 the trends displayed by the 8 coefficients of the interpolating function, some behaviors are
364 predicted. We underline that if year 2017 is neglected, the average annual emissions are reducing
365 respect to time. The obtained results are applied to the special case of a residential heat pump
366 installed in a building in Milan displaying a very good agreement, with a maximum error of 1.8%
367 for heating season and 1.4% for cooling. Even lower values of the error are seen if the average
368 approximating function is utilized. A comparison with the case of a constant emission factor is
369 presented as well. Further investigations will suggest the evaluation of control strategies, in order
370 to manage heat pumps utilization when the model suggest a GHG emissions reduction, mainly
371 when the power grid requires less fossil fuels consumption. Moreover, when more years will be
372 available the comparison may help evaluating if the actual transition to the renewable energies
373 induces variations in the general trend of the coefficients.

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