Journal of Urban and Environmental Engineering, v.12 , n.2 , p.172-187

ISSN 1982-3932
doi: 10.4090/juee.2018.v12n2.172187

Journal of Urban and Environmental Engineering

www.journal-uee.org

A PREDICTIVE MODEL FOR THE ESTIMATION OF CARBON DIOXIDE EMISSIONS OF MAGNETIC RESONANCE IMAGING (MRI) UNITS AND COMPUTED TOMOGRAPHY (CT) SCANNERS

Giorgos P. Kouropoulos

Department of Energy Technology Engineering, Faculty of Technological Applications
Technological Educational Institution of Athens, Greece

Received 03 October 2018; received in revised form 13 November 2018; accepted 03 December 2018

Abstract: The scope of the specific study is the statistical prediction of the annual carbon dioxide use emissions due to the operation of computed tomography (CT) scanners and magnetic resonance imaging (MRI) units in hospitals, health units and diagnostic centers, for the period between 2018 and 2030, in 120 countries across the world. The main sources of information for this study comprise statistical data from international organizations, scientific articles and measurements. The basic calculation tool of the study is a mathematical model, modified in such a way so that the calculations can be carried out using the available statistical data. In the final stage of the study, the functions that predict the carbon dioxide use emissions in relation to the years, will be extracted. Furthermore, all the errors and uncertainties of the mathematical model will be estimated. The conclusion, arising after implementation of the calculations, is that the carbon dioxide use emissions of CT scanners and MRI units are expected to grow by 30%, i.e., from 0.344 gigatonnes in 2018 to 0.497 gigatonnes in 2030.

Keywords: CT scanner; MRI unit; carbon dioxide; energy consumption; CO2 emissions

INTRODUCTION

In recent years, the increase of carbon dioxide emissions in the atmosphere has contributed to the deterioration of the greenhouse effect. Carbon dioxide corresponds to 65% of total global greenhouse gas emissions (IPCC, Carbon dioxide emissions from the energy sector amount to 32.1 $\times 10^9$ tonnes CO_2 (IEA, 2017). The Health Services sector is also important in terms of energy consumption and carbon dioxide emissions. Indicatively, hospitals require sustainable temperature conditions due to the presence of patients and people with health problems, and HVAC systems must operate almost all day, irrespective of the season. Also, certain type of medical equipment and devices, such as CT scanners and MRI units, require significant power. The level of their average energy consumption is quite significant, and their relevant carbon dioxide emissions are worth investigating.

Measurements that were conducted jointly by the World Health Organization & the International Federation of Home Economics, on a set sample of hospitals, showed that the total carbon dioxide use emissions in hospitals amount to 142.56 Kg CO_2/m^2 per year or 20,907 Kg CO_2/bed per year (Merlevede, 2013). Measurements that were conducted in healthcare institutions in Europe, showed that the average installed power of HVAC systems varied between 11 – 60kW/bed or 0.12 – 0.5 kW/m^2. The average power of lamps varied between 2 – 6 kVA/bed (Merlevede, 2011). The cost of energy consumption for the healthcare section amounted to $8.8 billion, for 2010 (Esmaeili *et al.*, 2011). Determination of the amount of emitted carbon dioxide in the atmosphere due to the operation of a piece of equipment, was mainly based on the carbon footprint of the specific equipment.

According to the resulting data, after searching on the scopus and sciencedirect databases, the term "carbon footprint" appears in the relevant literature, in 2005 (Wiedmann and Minx, 2008). "Ecological footprint" is the predecessor of carbon footprint, and the term was proposed by W.E. Rees (1992). There is no specific definition of "carbon footprint" and each scientist provides a somewhat different definition (Grubb and Ellis, 2007; Patel, 2006; Wiedmann and Minx, 2008).

In the specific study, carbon footprint is defined as the ratio of the mass of carbon dioxide emitted into the atmosphere due to the operation of the CT scanner and/or MRI unit to the time elapsing of a specific operation cycle of the CT scanner and/or MRI unit or to the energy saving of the CT scanner and/or MRI unit. More information concerning the methodology of calculations of emitted carbon dioxide, as well as the remaining processes, is defined by GHG Protocol Calculation Tools and the guidelines for national GHG inventories of IPCC (Bhatia, 2008; IPCC, 2006). According to "Industrial Processes and Product Use" (IPCC, 2006), the total carbon emissions "CE" of a piece of equipment are defined as the sum of the following carbon emissions:

$$CE_T = CE_M + CE_I + CE_U + CE_D \quad (1)$$

This study only examined equipment use carbon emissions CE_U for CT scanners and MRI units. According to the hybrid approach method (IPCC, 2006), the use carbon emissions of a piece of equipment are equal to:

$$CE_{U_{YC}} = \overline{EC} \times EF \quad (2)$$

The number of CT scanners and MRI units in some countries

CT scanners and MRI units are used extensively in medical imaging, for the purposes of health diagnosis. The number of specific diagnostic medical devices has increased from 1990 to 2009 (OECD, 2011). Also, over the past ten years, the use of these devices for computed and magnetic tomographies has increased (Bindman *et al.*, 2008).

According to the statistical data of the Organisation for Co-operation and Development, there are more than 31,861 MRI units or 20,192 MRI units per million population and 48,493 CT scanners or 30,464 CT scanners per million population in 34 countries for 2015, with the exception of China (OECD, 2017a; OECD, 2017b). There are more than 10,000 CT scanners in China (Wang *et al.*, 2016) and the number of CT scanners has increased by 45.3%.s MRI units show a similar increase (He *et al.*, 2013). In addition, according to other sources, China has approximately 1 CT scanner per 1.37 – 8.52 million population and India has approximately 1 CT scanner per 11.55 – 26.69 million population (Ciarmiello and Mansi, 2016).

The information regarding the number of CT scanners and MRI units for 36 OECD countries was derived from OECD 2012, OECD 2013, and OECD 2017; the information for the remaining countries of the world was derived from the Global Health Observatory data repository of the World Health Organization, for the period 2010 – 2014 (Kabongo *et al.*, 2015; WHO, 2016). The values of specific carbon dioxide emission coefficients are derived from the Covenant of Mayors of the European Union for 23 European countries and from Brander (2011) for the sample's remaining 97 countries. Concerning China and India, two of the world's most populous countries, there are no reliable and precise data regarding the number of CT scanners and MRI

units for each year. There are only approximate values per million residents. OECD provides the values about the number of examinations on medical devices for 23 countries (OECD, 2014a; OECD, 2014b). The values for the remaining 97 countries have been approximately determined, using linear interpolation and regression analysis according to **Eq. (5a)** and **(5b)**.

MATERIALS AND METHODS

Progress of the research

The estimation process of carbon dioxide use emissions of CT scanners and MRI units and the research progress are analytically described in the following steps **(Fig. 1**).

(a) Estimation of the number of medical devices and the number of examinations that were carried out on CT scanners and MRI units in 120 countries with 6.08 billion population for 2013 (United Nations, 2013). The number of examinations of each country is estimated, for the period between 2010 and 2016.
(b) Estimation of the average energy consumption per examination on the CT scanners and MRI units.
(c) Determination of the specific electricity factor of the generation system of each country (Brander *et al.*, 2011; Covenant of Mayors of EU).
(d) Calculation of the number of examinations that were carried out on CT scanners and MRI units for the countries with available statistical data (OECD, 2014a; OECD, 2014b).
(e) Calculation of carbon dioxide use emissions of CT scanners and MRI units for the countries with available statistical data by applying **Eq. 3**.
(f) Determination of $NE_{YC}{}'/\overline{NE_{OECD}}$ ratio according to equations (5a), (5b) and approximate calculation of the number of examinations that were carried out using the medical devices, for the countries with unavailable statistical data.
(g) Calculation of carbon dioxide use emissions of CT scanners and MRI units for the countries with unavailable statistical data, by applying **Eq. 3**.
(h) Calculation of total carbon dioxide emissions of 120 countries from 2010 to 2016, by applying **Eq. 6**. See **Tables 6–7** in appendix.
(i) Extraction of the functions $CE_{U_{MRI}}(t)$ and $CE_{U_{CT}}(t)$, using regression analysis and the curves in **Figs 4–6**.
(j) Estimation of the errors and uncertainties calculated by **Eqs. 9–18**. Calculation of the total uncertainty of the model carried out by applying **Eq. 18**.

Estimation of the average energy consumption of CT scanners and MRI units

The estimation of the average energy consumption of a device is a basic step for the determination of emitted carbon dioxide due to the operation of this device. With regard to the CT scanners and MRI units, it is very difficult to determine the average energy consumption with precision, because these devices do not have constant power during turn-on. In addition, there are different types and technologies for these devices, with different power levels and differentiation in energy consumption. The search for information about the energy consumption per examination of the abovementioned medical devices is a good practice for determining the consumption with lower uncertainty.

According to Herrmann and Rock (2012), measurements that were carried out on various MRI units with different consumption and operation profiles, show that the average energy consumption amounts to 15.3 kWh per patient or examination. Measurements carried out by COCIR (2012), show that the average energy consumption of MRI units amounts to 9.6 kWh per patient or examination. The energy consumption-time curves of MRI units that were extracted in the technical report by NREL (Sheppy *et al.* 2014), show that the first MRI unit consumes about 356.2 kWh and the second MRI unit consumes about 268.3 kWh and 286.7 kWh for two different operation days. Considering that the average time of examination, using the MRI unit, varied between 30 to 45 minutes (Bushong, 2003) and the time-lapse between two examinations is 10 m., it becomes apparent that the average time per patient or examination is 47.5 m. The abovementioned energy consumptions are standardized at 25.8 kWh/examination for the first MRI unit, 11.8 kWh/examination and 11.7 kWh/examination for the second MRI unit, with two different operation profiles. Based on the above data, it can be concluded that the average energy consumption for MRI units is 15.63 ± 22.96% kWh per patient or examination.

With regard to the energy consumption of CT scanners, measurements carried out on three CT scanners (Heye *et al.*, 2017), show that the average energy consumption amounts to 2.1 kWh/examination. Measurements on two other CT scanners, show that the average energy consumption amounts to 13.04 kWh/patient or examination and 6.71 kWh/patient or examination (Twomey *et al.*, 2012). The energy consumption - time curves of three CT units, according to the technical report by NREL (Sheppy *et al.* 2014), show that the average energy consumption of the three CT scanners amounts to 69.6 kWh, 102 kWh and 238.8 kWh respectively. Taking under consideration the average time of examination in the CT scanner is 30 m.

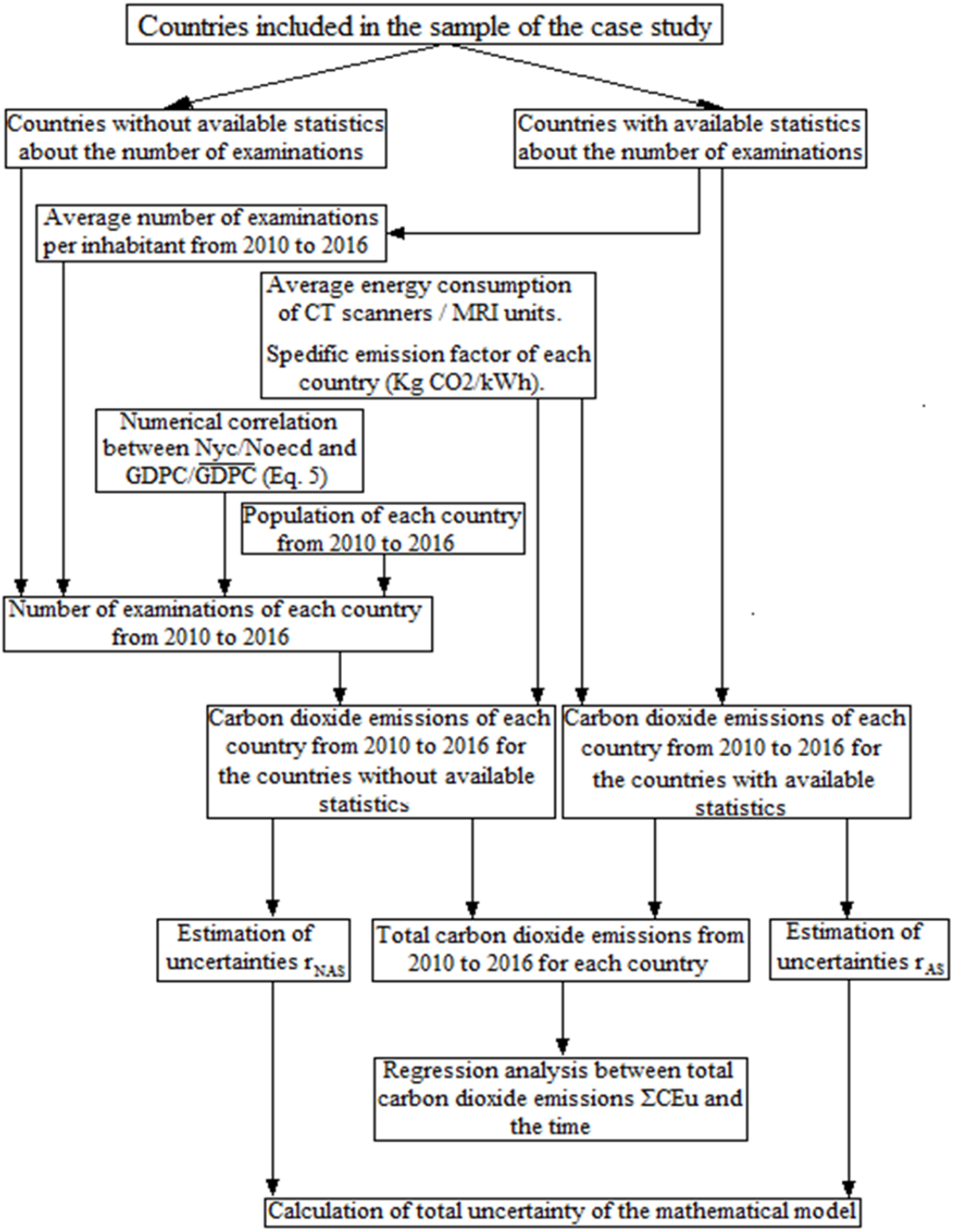

Fig. 1 Progress of calculations.

Table 1. The values regarding average energy consumption per examination

A/A	MRI units (kWh/exam)	CT scanners (kWh/exam)
1	15.3	2.1
2	9.6	13.74
3	25.8	6.71
4	11.8	1.9
5	11.7	2.8
6	–	6.6
Avg.	15.63	5.53
$r_{\overline{ECP}}$	± 22.96%	± 31.55%

(Herts *et al.*, 1998) and the time-lapse between two examinations is 10 m., it becomes apparent that the average time per patient or examination is 40 m. The abovementioned CT scanner energy consumptions are standardized at 1.9 kWh/examination, 2.8 kWh/examination and 6.6 kWh/examination respectively. Based on the above data, it can be concluded that the average energy consumption for CT units is 5.53 ± 31.55% kWh per patient or examination.

Application of modified mathematical model

The present study utilizes the application of a modified model of **Eq. (2)** for the estimation of carbon dioxide emissions. The specific model has been modified in such a way that the calculation of carbon dioxide emissions can be carried out, using available statistical data. According to the model:

$$CE_{U_{YC}} = \overline{ECP} \times NE_{YC} \times EF_C \tag{3}$$

Countries with unavailable statistics

If value NE_{YC} is not available via statistics, the number of examinations carried out using the medical device, is approximately calculated as a function of the Gross Domestic Product per Capita of each country.

$$\frac{NE_{YC}{}'}{\overline{NE_{OECD}}_{Y}} = f\left(\frac{GDPC}{\overline{GDPC}}\right) \Leftrightarrow$$
$$\Leftrightarrow NE'_{YC} = \overline{NE_{OECD}}_{Y} \times f\left(\frac{GDPC}{\overline{GDPC}}\right) \Leftrightarrow \tag{4}$$
$$\Leftrightarrow NE_{YC} = \frac{NP_{YC} \times \overline{NE_{OECD}}_{Y}}{1000} f\left(\frac{GDPC}{\overline{GDPC}}\right)$$

The numerical relationship between dimensionless ratio $GDPC/\overline{GDPC}$ and $NE_{YC}{}'/\overline{NE_{OECD}}$ ratio is governed by **Eqs. 5a–5b.** Regression analysis in **Figs 2–3**. These functions were the result of regression analysis in the available statistical data of 23 OECD countries.

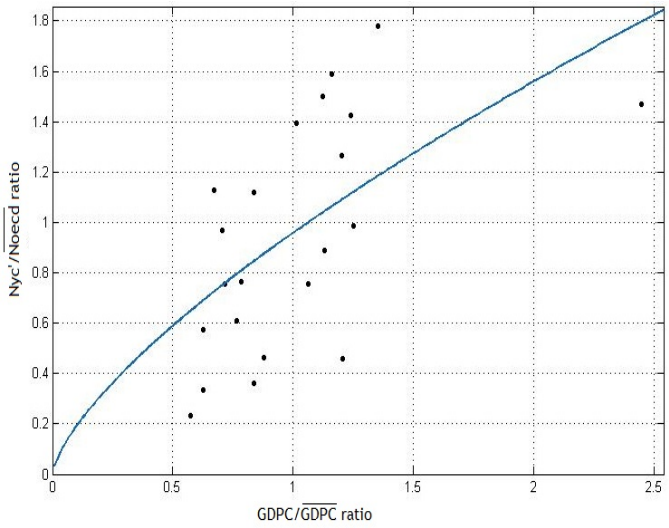

Fig. 2 Regression analysis between $GDPC/\overline{GDPC}$ ratio and $NE_{YC}{}'/\overline{NE_{OECD}}$ ratio for MRI units, r^2=0.365.

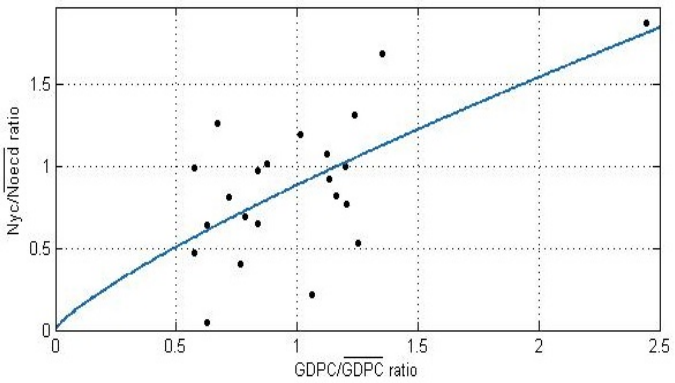

Fig. 3 Regression analysis between $GDPC/\overline{GDPC}$ ratio and $NE_{YC}{}'/\overline{NE_{OECD}}$ ratio for CT scanners, r^2=0.377.

Basic restriction for the above functions, **Eqs. 5a–5b**, $0 \leq GDPC/\overline{GDPC} \leq 2.5$. The dimensionless ratio for MRI units is equal to:

$$\frac{NE_{YC}{}'}{\overline{NE_{OECD}}_{Y}} = 0.9579\left(\frac{GDPC}{\overline{GDPC}}\right)^{0.703} \tag{5a}$$

The dimensionless ratio for CT scanners is equal to:

$$\frac{NE_{YC}{}'}{\overline{NE_{OECD}}_{Y}} = 0.8838\left(\frac{GDPC}{\overline{GDPC}}\right)^{0.8026} \tag{5b}$$

The total carbon dioxide emissions due to the operation of CT scanners and MRI units for a number of 120 countries is equal to:

$$\sum_{C=1}^{120} CE_{U_{YC}} = CE_{U_{Y,1}} + \cdots + CE_{U_{Y,120}} \tag{6}$$

Table 2. Average number of MRI and CT examinations per 1000 population for the sample of 23 countries of the OECD.

Year	$\overline{NE_{OECD}}$ (MRI exams per 10^3)	$\overline{NE_{OECD}}$ (CT exams per 10^3)
2010	49.6	123.6
2011	52.9	130.4
2012	56.1	133.5
2013	60.0	142.6
2014	63.7	148.7
2015	67.5	149.9
2016	71.2	158.8

The Y indicator corresponds to the different year between 2010 and 2016, the C indicator corresponds to the country. The country in the first position of **Tables 5–6** is shown as number 1 and the country in the last position is shown as number 120. The **Eq. 7** represents the correlation between total carbon dioxide emissions in relation to the years after the conduct of the regression analysis.

$$CE_U(t) = f\left(\sum_{C=1}^{120} CE_{U_{YC}}\right)(t) \pm r_R \quad (7)$$

ERRORS AND UNCERTAINTIES

Every calculation of the carbon dioxide emissions of each country reveals an error that is propagated and possible to estimate.

$$\sum_{C=1}^{120} CE_{U_{YC}}\left(1 \pm r_{s_{YC}}\right) = \\ = CE_{U_{Y,1}}\left(1 \pm r_{s_{Y,1}}\right) + \cdots + CE_{U_{Y,120}}\left(1 \pm r_{s_{Y,120}}\right) \quad (8)$$

With regard to the countries with unavailable statistics on the number of examinations, there exist the following errors, propagated in **Eq. (3)**:

$$(CE_U + r_{s_{NAS}}) = (\overline{ECP} \pm r_{\overline{ECP}})(NE \pm r_{NE})EF_C$$
$$\Leftrightarrow r_{s_{NAS}} = \sqrt{r_{\overline{ECP}}^2 + r_{NE}^2} \quad (9)$$

For equation (4):

$$NE + r_{NE} = \frac{0.957(NP \pm r_{NP})\left(\overline{NE_{OECD}} \pm r_{\overline{OECD}}\right)}{1000} \times \left(\frac{GDPC}{\overline{GDPC} + r_{GDPC}}\right)^{0.703}(1 \pm r_{rat}) \Leftrightarrow \quad (10)$$
$$\Leftrightarrow r_{NE} = \sqrt{r_{NP}^2 + r_{\overline{OECD}}^2 + r_f^2 + r_{rat}^2}$$

With the replacement of **Eq. (10)** by **Eq. (9)**, we have the following form:

$$r_{s_{NAS}} = \sqrt{r_{\overline{ECP}}^2 + r_{NP}^2 + r_{\overline{OECD}}^2 + r_{GDPC}^2 + r_{rat}^2} \quad (11)$$

Calculation of r_{GDPC} with regard to the MRI units, **Eqs. (5a) and (5b):**

$$\frac{\delta f(\overline{GDPC})}{\delta_{GDPC}} = 0.703\left(\frac{GDPC}{\overline{GDPC}}\right)'\left(\frac{GDPC}{\overline{GDPC}}\right)^{0.703} \Leftrightarrow \\ \Leftrightarrow r_{GDPC}^2 = 0.494\frac{GDPC^{1.406}}{\overline{GDPC}^{3.406}} \quad (12)$$

Calculation of r_{GDPC} with regard to the CT scanners:

$$\frac{\delta f(\overline{GDPC})}{\delta_{GDPC}} = 0.8026\left(\frac{GDPC}{\overline{GDPC}}\right)'\left(\frac{GDPC}{\overline{GDPC}}\right)^{0.8026} \Leftrightarrow \\ \Leftrightarrow r_{GDPC}^2 = 0.644\frac{GDPC^{1.406}}{\overline{GDPC}^{3.406}} \quad (13)$$

With regard to the countries with available statistics on the number of examinations, the following errors exist in **Eq. (3):**

$$(CE_U + r_{s_{AS}}) = (\overline{ECP} \pm r_{\overline{ECP}}) \times NE \times EF_C \Leftrightarrow$$
$$\Leftrightarrow \frac{\delta_s}{|CE_U|} = \sqrt{\left(\frac{\delta_{\overline{ECP}}}{\overline{ECP}}\right)^2} \Leftrightarrow r_{s_{AS}} = r_{\overline{ECP}} \quad (14)$$

It is concluded that the errors among the 23 countries with available statistics on the number of examinations are the same and the errors among the 97 countries with unavailable statistics are also the same. Consequently, **Eq. (8)** can be written as follows:

$$\left(1 \pm r_{s_T}\right)\sum_{C=1}^{120} CE_{U_{YC}} = \\ \left(1 \pm r_{s_{AS}}\right)\sum_{C=1}^{23} CE_{U_{YC}} + \left(1 \pm r_{s_{NAS}}\right)\sum_{C=77}^{120} CE_{U_{YC}} \quad (15)$$

The total error of the calculations of carbon dioxide emissions of CT scanners or MRI units for each year can be determined by the following equation:

$$r_{s_T} = \sqrt{r_{s_{AS}}^2 + r_{s_{NAS}}^2} \overset{(14)}{\overset{(11)}{\Longleftrightarrow}}$$
$$r_{s_T} = \sqrt{2r_{\overline{ECP}}^2 + r_{NP}^2 + r_{\overline{OECD}}^2 + r_{GDPC}^2 + r_{rat}^2} \quad (16)$$

The error r_{rat} is calculated as:

$$r_{rat} = 1 - \sqrt{r_c} \quad (17)$$

The abovementioned errors and mathematical relations are the same for CT scanners and MRI units. The total uncertainty of the model after the sum of carbon dioxide emissions of CT scanners and MRI units is calculated by **Eq. (18)**:

$$TU_{(CT+MRI)} = \sqrt{r_{s_{T(CT)}}^2 + r_{s_{T(MRI)}}^2} \quad (18)$$

RESULTS AND DISCUSSION

The proposed modified model for the prediction of carbon dioxide use emissions is a theoretical model, based on the available statistics and has not been investigated by researchers. In addition, this model is designed in such way as to receive and utilize OECD statistical data on the number of examinations using CT scanners and MRI units. The main advantage of this model is the possibility to estimate errors and uncertainties, but its disadvantage is the resulting high level of uncertainty. Further investigation of the model is necessary in the future.

The total estimated uncertainty is high. This is both due to the low number of countries with available statistics regarding the number of examinations using the medical devices per 1,000 population, as well as the low correlation coefficient in (5a) (5b) and the high standard error of measurements regarding the average energy consumption per examination of CT scanners and MRI units. These three errors contribute to the total uncertainty at approximately 95.7% for MRI units and 94% for CT scanners. Calculations for the present study utilized the population and GDP per capita for 2013. This was done in order to ensure less calculations and complexity.

Table 3. Aggregated data of the errors.

Type of error (%)	MRI Units (%)	CT Scanners (%)
$r_{\overline{ECP}}$	22.96	31.55
$r_{\overline{OECD}}$	10.7	14.9
r_{rat}	39.58	38.6
r_{NP}	0.96	
$r_{s_{AS}}$	22.96	31.55
$r_{s_{NAS}}$	47.0	52.0
r_{s_T}	52.3	60.9
r_R	0.00084	0.0098
TU	80.3	

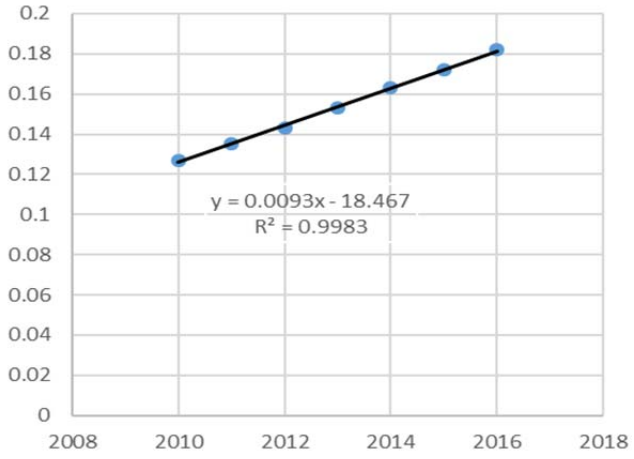

Fig. 4 Total carbon dioxide emissions ($\times 10^{12}$ kg) due to the operation of MRI units for 120 countries in relation to time, r^2=0.9983.

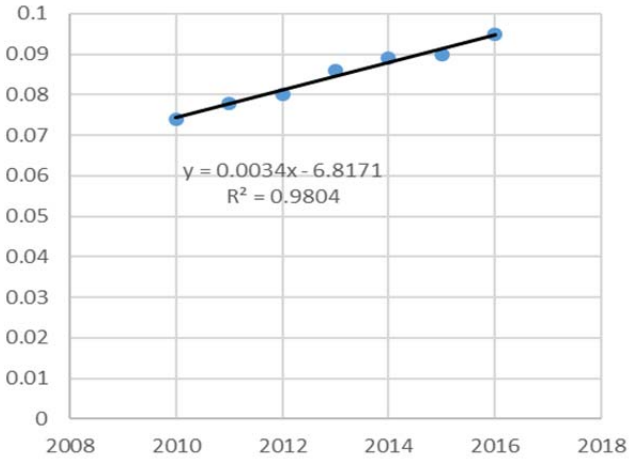

Fig. 5 Total carbon dioxide emissions ($\times 10^{12}$ kg) due to the operation of CT scanners for 120 countries in relation to time, r^2=0.9804.

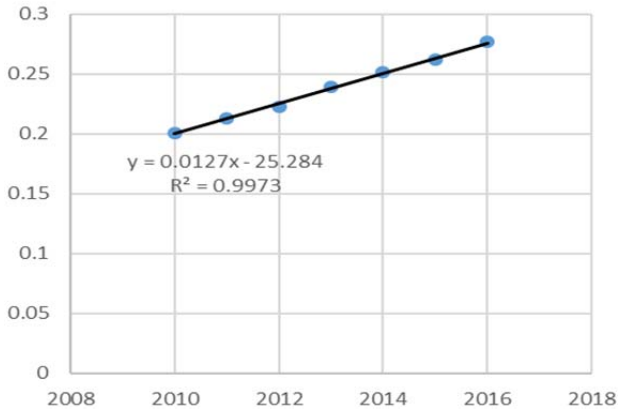

Fig. 6 Total carbon dioxide emissions ($\times 10^{12}$ kg) for the joint operation of CT scanners and MRI units for 120 countries, in relation to time, r^2=0.9973.

Table 4. Participation rate of carbon dioxide use emissions due to the operation of MRI units and CT scanners in 120 countries from 2010 to 2016 (Global Carbon Atlas; Boden *et al.*, (2017); UNFCCC, (2017); BP, (2017)).

Year	Global CO2 emissions (GtC)	$CE_{U_{MRI+CT}}$ (GtC)	Participation rate of CO2 emissions (%)
2010	33.4	0.201	0.602
2011	34.8	0.213	0.612
2012	35.4	0.223	0.63
2013	35.8	0.239	0.668
2014	36.1	0.252	0.698
2015	36.0	0.262	0.728
2016	36.2	0.277	0.765

Table 5. Aggregated data of the total carbon dioxide emissions due to operation of MRI units and CT scanners for 120 countries from 2010 to 2016 (GtC).

Year	MRI units (GtC)	CT scanners (GtC)	Sum (GtC)
2010	0.127	0.074	0.201
2011	0.135	0.078	0.213
2012	0.143	0.080	0.223
2013	0.153	0.086	0.239
2014	0.163	0.089	0.252
2015	0.172	0.090	0.262
2016	0.182	0.095	0.277

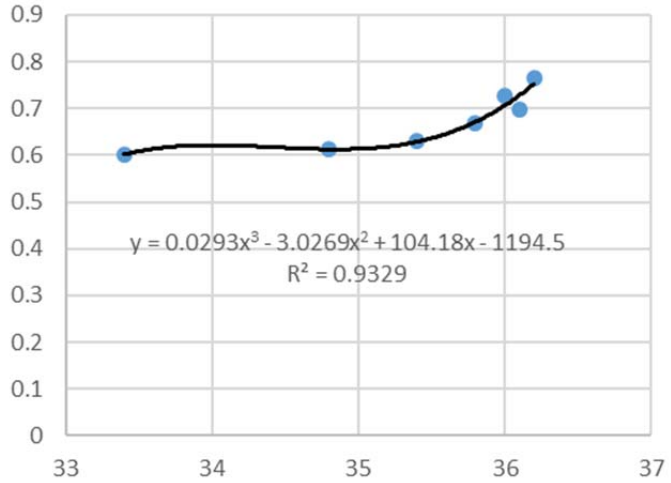

Fig. 7. Numerical correlation between global carbon dioxide emissions "GCD" ($\times 10^{12}$ kg) and participation rate of carbon dioxide emissions of MRI units and CT scanners in 120 countries from 2010 to 2016, r^2=0.9329.

There are the following regression functions:

Fig. 4 $$CE_{U_{MRI}}(t) = 0.0093t - 18.467 \quad (19)$$

Fig. 5 $$CE_{U_{CT}}(t) = 0.0034t - 6.8171 \quad (20)$$

Fig. 6 $$CE_{U_{MRI+CT}}(t) = 0.0127t - 25.284 \quad (21)$$

Basic restriction for **Eqs. 19–21**, $t \geq 2010$.

$$PR(\text{GCD}) = 0.0293GCD^3 - 3.0269GCD^2 + \\ +104.18GCD + 1194.5 \quad (22)$$

CONCLUSIONS

After the implementation of the proposed model's calculations regarding carbon dioxide emissions, there exists a high degree of positive correlation and emissions increase linearly in relation to time. The total carbon dioxide use emissions of MRI units and CT scanners amounted to 0.277 GtC in 2016 for 120 countries, a number corresponding to 0.77% of global carbon dioxide emissions for 2016.

The carbon dioxide emissions of MRI units increased about 4.9% per year and the emissions of CT scanners increased about 3.6% per year. The carbon dioxide emissions for the joint operation of MRI units and CT scanners increased about 4.7% per year and are expected to grow cumulatively by 30.8% from 2018 to 2030, in 120 countries. Specifically, according to the results, carbon dioxide emissions are estimated to increase, from 0.344 gigatonnes in 2018, to 0.497 gigatonnes in 2030. For 2018, 56.6 Kg CO_2 correspond to each inhabitant in the 120 countries of the sample. In addition, the change in the participation rate of carbon dioxide emissions for MRI units and CT scanners, in relation to global carbon dioxide emissions, may be governed by a 2nd or higher order polynomial equation.

NOMENCLATURE – ABBREVIATIONS

CE_M: Equipment manufacturing carbon emissions.

CE_I: Equipment installation carbon emissions.

CE_U: Equipment use carbon emissions.

CE_D: Equipment disposal and final carbon emissions.

$\overline{EC}$: The average energy consumption of equipment in kWh.

EF: The carbon dioxide emissions of country in Kg CO_2/kWh.

Y: The year.

C: The country

$\overline{ECP}$: The average energy consumption per examination of device in kWh.

NE_{YC}: The number of examinations that carried out in the medical device for each year and country.

EF_C: The specific carbon dioxide emission coefficient of each country in Kg CO_2/kWh.

$\overline{NE_{OECD}}_Y$: Average number of MRI and CT examinations per 1000 population for the countries with available statistics [25 – 26].

NE_{YC}': The estimated number of examinations that carried out in the device per 1000 population for each year and country.

NP_{YC}: The population of each country for 2013.

$GDPC$: The gross domestic product per capita of each country in dollars for 2013 [35 – 36].

$\overline{GDPC}$: The average gross domestic product per capita of the OECD countries for 2013 (38936$).

$r_{s_{YC}}$: The total error that corresponds in the calculation of each country and year.

r_R: The error of the final function of regression analysis.

δ: Symbolizes the absolute error.

r_c: The correlation coefficient of equations (5a) and (5b).

$r_{s_{AS}}$: The error (%) that corresponds to the 23 countries with available statistics.

$r_{s_{NAS}}$: The error (%) that corresponds to the 97 countries with unavailable statistics.

r_{s_T}: The total error (%) of calculations.

$r_{\overline{ECP}}$: The standard deviation (%) of the average energy consumption per examination of MRI units and CT scanners that was calculated in the present study.

r_{NE}: The average standard deviation (%) of the number of examinations in MRI units and CT scanners for the countries without available statistical data.

$r_{\overline{OECD}}$: The standard deviation (%) of the average number of MRI and CT examinations per 1000 population of the sample of the OECD countries with available statistical data.

r_{rat}: This error concerns the equations (5a) (5b) and calculated by (17).

r_{NP}: The error (%) due to the variation of population from 2010 to 2016.

r_{GDPC}: The error (%) due to the variation of gross domestic product per capita of world and each country from 2010 to 2016.

TU: Total uncertainty of the model.

PR: Participation rate (%).

GCD: Global carbon dioxide emissions (GtC)

GtC: Gigatonnes of carbon emissions.

REFERENCES

Bhatia, P. (2008). Methodologies for measuring the carbon footprint, ICTs and Climate Change. International Symposium, 17-18 June, BT Centre Auditorium, London. https://www.itu.int/dms_pub/itu-t/oth/06/0F/T060F0000090023PDFE.pdf (Accessed on 14 April 2018).

Bindman, R.S., Miglioretti, D.L. and Larson, E.B. (2008). Rising use of diagnostic medical imaging in a large integrated health system. Health Affairs, 27(6), 1491-1502. doi: 10.1377/hlthaff.27.6.1491

Boden, T.A., Marland, G. and Andres, R.J. (2017). Global, Regional, and National Fossil-Fuel CO2 Emissions, Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA. doi: 10.3334/CDIAC/00001_V2017.

BP (2017). Statistical Review of World Energy. http://www.bp.com/en/global/corporate/energy-economics.html (Accessed on 14 April 2018).

Brander, M., Sood, A., Wylie, C., Haughton, A. and Lovell, J. (2011). Technical Paper, Electricity-specific emission factors for grid electricity. Ecometrica. https://ecometrica.com/assets/Electricity-specific-emission-factors-for-grid-electricity.pdf (Accessed on 14 April 2018).

Bushong, S.C. (2003). Magnetic resonance imaging: Physical and biological principles, 3rd edition, Mosby, ISBN 0-323-01485-2.

Ciarmiello, A. and Mansi, L. (2016). PET-CT and PET-MRI in Neurology: SWOT Analysis Applied to Hybrid Imaging. 1st ed. Springer, Switzerland. http://doi.org/10.1007/978-3-319-31614-7

COCIR, (2012). Magnetic resonance equipment measurement of energy consumption 2011, European Cordination Committee of the Radiological Electromedical and Healthcare IT Industry. http://www.cocir.org/fileadmin/6_Initiatives_SRI/Measurement/COCIR_SRI_-_MRI_measurement_of_energy_consumption_2012.pdf (Accessed on 14 April 2018).

Esmaeili, M.A., Twomey, J., Yildirim, B., Overcash, M., Jahromi, A., Thomas, N., Mcadam, A. and Dominquez, F. (2011). Environmental impacts of healthcare services: Delivery of x-ray services. IEEE International Symposium of Sustainable Systems and Technology (ISSST), 16-18 May, Chicago, IL, USA. doi: 10.1109/ISSST.2011.5936905

Global Carbon Atlas. http://www.globalcarbonatlas.org/en/CO2-emissions (Accessed on 14 April 2018).

Grubb, E. and Ellis, C. (2007). Meeting the carbon challenge: The role of commercial real estate owners, Users & Managers, Chicago.

He, D., Yu, H. and Chen, Y. (2013). Equity in the distribution of CT and MRI in China: A panel analysis. International Journal for Equity in Health, 12(39), 1-15. doi: 10.1186/1475-9276-12-39 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3682935/ (Accessed on 14 April 2018).

Herrmann, C. and Annekristin, R. (2012). Magnetic resonance Equipment (MRI) – Study on the potential for environmental improvement by the aspect of energy efficiency, PE INTERNATIONAL AG, Report.
http://cocir.org/fileadmin/6_Initiatives_SRI/SRI_Status_Report/pe_international_-_improvement_potentials_for_mri.pdf (Accessed on 14 April 2018).

Herts, R.B., Perl, J., Seney, C., Lieber, M.L., Davros, W.J. and Baker, M.E. (1998). Comparison of examination times between CT scanners: Are the newer scanners faster?, American Journal of Roentgenology, 170(1), 8-13. https://doi.org/10.2214/ajr.170.1.9423589

Heye, T., Loser, M., Degen, M., Brodbeck, D., Basel, C.H., Erlangen, D.E. and Muttenz, C.H. (2017). The carbon footprint of radiology – measuring energy consumption of CT scanners and identifying opportunities for energy saving, European Society of Radiology ECR2017. https://doi.org/10.1594/ecr2017/C-

IEA (2017). IEA finds CO2 emissions flat for third straight year even as global economy grew in 2016. https://www.iea.org/newsroom/news/2017/march/iea-finds-co2-emissions-flat-for-third-straight-year-even-as-global-economy-grew.html (Accessed on 14 April 2018).

IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (Accessed on 14 April 2018).

IPCC (2014). Climate Change 2014: Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlomer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf (Accessed on 14 April 2018).

Kabongo, M.J., Nel, S. and Pitcher, R.D. (2015). Analysis of licensed South African diagnostic imaging equipment. The Pan African Medical Journal, 22, 57. https://doi.org/10.11604/pamj.2015.22.57.7016

Merlevede, P. (2011). Energy in European healthcare institutions. International Federation of Hospital Engineering – Europe. VTDV Belgium. http://www.vtdv.be/l/library/download/urn:uuid:89a530f9-41fc-4b9f-9c60-32924038a7c8/bern+2013+energy++in+european+healthcare+institutions+2.pdf?format=save_to_disk&ext=.pdf (Accessed on 14 April 2018).

Merlevede, P. (2013). Energy in healthcare. Global Forum Medical Devices - WHO. International Federation of Hospital Engineering. http://www.who.int/medical_devices/Sat_am_HC_7_MERLEVEDE.pdf?ua=1 (Accessed on 14 April 2018).

OECD (2011). Number of magnetic resonance imaging (MRI) units and computed tomography (CT) scanners: Selected countries, selected years 1990 - 2009. https://www.cdc.gov/nchs/data/hus/2011/123.pdf (Accessed on 14 April 2018).

OECD (2012). Health at a Glance: Europe 2012, OECD Publishing. http://dx.doi.org/10.1787/9789264183896-en (Accessed on 14 April 2018).

OECD (2013). Health at a Glance: OECD Indicators, OECD Publishing. http://dx.doi.org/10.1787/health_glance-2013-en (Accessed on 14 April 2018).

OECD (2014a). Computed tomography (CT) exams, total Per 1000 population. OECD Health Data: Health care resources: OECD Health Statistics (database). doi: 10.1787/ct-exams-tot-table-2014-1-en https://www.oecd-ilibrary.org/social-issues-migration-health/computed-tomography-ct-exams-total-2014-1_ct-exams-tot-table-2014-1-en (Accessed on 14 April 2018).

OECD (2014b). Magnetic resonance imaging (MRI) exams, total Per 1000 population. OECD Health Data: Health care resources: OECD Health Statistics (database). doi: 10.1787/mri-exam-total-table-2014-1-en https://www.oecd-ilibrary.org/social-issues-migration-health/magnetic-resonance-imaging-mri-exams-total-2014-1_mri-exam-total-table-2014-1-en (Accessed on 14 April 2018).

OECD (2017a). Magnetic resonance imaging (MRI) units (indicator). doi: 10.1787/1a72e7d1-en https://data.oecd.org/healtheqt/magnetic-resonance-imaging-mri-units.htm (Accessed on 14 April 2018).

OECD (2017b). Computed tomography (CT) scanners (indicator). doi: 10.1787/bedece12-en https://data.oecd.org/healtheqt/computed-tomography-ct-scanners.htm#indicator-chart (Accessed on 14 April 2018).

OECD (2018). Gross domestic product (GDP) (indicator). doi: 10.1787/dc2f7aec-en https://data.oecd.org/gdp/gross-domestic-product-gdp.htm (Accessed on 14 April 2018).

Patel, J. (2006). "Green sky thinking". Environment Business, (122): 32.

Rees, W.E. (1992). Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environment and Urbanization, 4(2), 121-130. https://doi.org/10.1177/095624789200400212

Sheppy, M., Pless, S. and Kung, F. (2014). Healthcare Energy End-Use Monitoring, National Renewable Energy Laboratory (NREL), Department of Energy Office of Energy Efficiency & Renewable Energy, Technical Report NREL/TP-5500-61064. https://www.nrel.gov/docs/fy14osti/61064.pdf (Accessed on 14 April 2018).

Technical annex to the SEAP template instructions document: The emissions factors. Covenant of Mayors. http://www.eumayors.eu/IMG/pdf/technical_annex_en.pdf (Accessed on 14 April 2018).

Twomey J. M., Overcash M., and Soltani S. (2012). Life Cycle for Engineering the Healthcare Service Delivery of Imaging. In: Dornfeld D., Linke B. (eds) Leveraging Technology for a Sustainable World. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-29069-5_23 (Accessed on 14 April 2018).

UNFCCC (2017). National Inventory Submissions 2017. United Nations Framework Convention on Climate Change. http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/9492.php; (Accessed on 14 April 2018).

United Nations, 2013. Department of Economic and Social Affairs, Population Division (2013). World Population Prospects: The 2012 Revision, Highlights and Advance Tables. Working Paper No. ESA/P/WP.228. https://esa.un.org/unpd/wpp/publications/Files/WPP2012_HIGHLIGHTS.pdf (Accessed on 14 April 2018).

Wang, L., Li, B.S., Zhu, W.Z. and Feng, X.Y. (2016). Rational use of computed tomography for individual health assessment in asymptomatic population: Chinese experience. Chinese Medical Journal, 129(3), 348-356. doi: 10.4103/0366-6999.174504

WHO, (2016). Global Health Observatory data repository. Medical equipment Data by country. http://apps.who.int/gho/data/node.main.510 (Accessed on 14 April 2018).

Wiedmann, T. and Minx, J. (2008). A definition of 'Carbon Footprint'. In: C.C. Pertsova, Ecological Economics Research Trends: Chapter 1, pp. 1-11, Nova Science Publishers, Hauppauge NY, USA. ISBN: 1-60021-941-1.

World Bank, International Comparison Program database. GDP per capita, PPP. https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?end=2016&start=2013 (Accessed on 14 April 2018).

APPENDIX

Table 5. Estimated carbon dioxide emissions for MRI units in tonnes

Countries	Population 2013, ($\times 10^6$)	GDPC($) 2013	Ratio (Eq. 5)	EF_C Kg CO2/kWh	2010	2011	2012	2013	2014	2015	2016
Afghanistan	30.55	1877.4	0.114	1.2138	3267	3485	3696	3953	4196	4447	4690
Albania	3.17	4414.7	0.207	0.0091	4.637	4.945	5.244	5.609	5.955	6.31	6.656
Argentina	40.54	12977	0.442	0.3919	5449	5812	6164	6592	6999	7416	7823
Angola	21.47	6400.7	0.269	0.3795	1700	1814	1923	2057	2184	2314	2441
Armenia	2.98	7997.4	0.315	0.1282	93.24	99.45	105.5	112.8	119.8	126.9	177.9
Australia*	23.34	-	-	0.9918	8394	8720	9407	9986	10456	10963	11506
Austria	8.5	50504.7	1.15	0.1768	1165	1243	1318	1409	1496	1585	1672
Azerbaijan	9.41	17172	0.539	0.3918	1540	1642	1742	1863	1978	2096	2210
Bangladesh	157.6	951.9	0.071	0.6371	5489	5854	6208	6639	7049	7469	7879
Belarus	9.36	7978.8	0.314	0.6109	1393	1486	1576	1685	1789	1896	2000
Belgium*	11.1	-	-	0.2248	2742	3003	3249	3510	3771	4033	4294
Belize	0.33	8179	0.32	0.2997	24.52	26.15	27.74	29.66	31.49	33.37	35.2
Bosnia & Herzegovina	3.83	5035.9	0.227	1.3262	895.6	955.2	1013	1083	1150	1219	1286
Botswana	2.02	16111	0.515	1.8257	1473	1571	1666	1782	1891	2004	2114
Brazil	200.36	15968	0.512	0.0926	7363	7853	8328	8907	9456	10020	10570
Brunei Darussalam	0.42	81827	1.615	0.8195	430.8	459.5	487.3	521.2	553.3	586.3	618.5
Bulgaria	7.22	7674.9	0.306	1.166	1996	2129	2258	2415	2564	2716	2865
Burkina Faso	16.93	1616.8	0.102	0.7358	988.2	1054	1118	1195	1269	1345	1419
Cambodia	15.14	3069.3	0.161	1.1708	2207	2354	2496	2669	2834	3003	3168
Cameroon	22.25	3208.3	0.166	0.2166	618.9	660.1	700	748.7	794.9	842.3	888.5
Canada*	35.18	-	-	0.1798	4577	4923	5309	5260	5596	5922	6248
Chile*	17.62	-	-	0.4086	956.5	1249	1384	1575	1755	1935	2127
China	1357	7077.8	0.289	0.9736	3E+05	3E+05	3E+05	4E+05	4E+05	4E+05	4E+05
Costa Rica	4.87	14513	0.479	0.0638	115.3	123	130.4	139.5	148.1	156.9	165.5
Côte d'Ivoire	20.32	2980.3	0.157	0.5112	1267	1351	1433	1532	1627	1724	1818
Croatia	4.29	13575	0.457	0.3865	587	626.1	664	710.1	753.9	798.9	842.7
Cuba	11.27	6760.2	0.28	0.9381	2293	2445	2593	2774	2945	3120	3291
Cyprus	1.14	27908	0.758	0.7717	516.9	551.3	584.7	625.3	663.9	703.5	742.1
Czech Republic*	10.7	-	-	0.9385	5274	6121	6780	7197	7752	8308	8862
Denmark*	5.62	-	-	0.3747	2001	2153	2205	2495	2690	2884	3078
Ecuador	15.74	11037	0.395	0.2696	1299	1385	1469	1571	1668	1768	1865
Egypt	82.06	10156	0.372	0.5001	11849	12637	13401	14333	15217	16125	17009
El Salvador	6.34	7902	0.312	0.2561	393	419.1	444.5	475.4	504.7	534.8	564.1
Eritrea	6.33	594	0.051	0.678	168.4	179.6	190.5	203.7	216.3	229.2	241.7
Estonia*	1.29	-	-	1.9069	1861	1769	1799	2233	2443	2652	2861
Ethiopia	94.1	1372	0.091	0.1189	790.8	843.4	894.5	956.6	1016	1076	1135
Finland*	5.43	-	-	0.2255	664.1	710	805.7	868.3	939.1	1010	1081
France*	64.29	-	-	0.0709	4289	4809	5842	5963	6448	6933	7419
Gabon	1.67	17078	0.537	0.4252	295.4	315.1	334.2	357.4	379.4	402.1	424.1
Gambia	1.85	1640	0.103	0.7358	109.1	116.3	123.4	131.9	140.1	148.4	156.6
Germany*	82.73	-	-	0.6722	82748	82748	82748	82748	82748	82748	82748

Greece*	11.13	-	-	1.9211	27738	25265	22592	22592	22592	22592	22592
Guyana	0.8	6931.4	0.285	0.2097	37.03	39.49	41.88	44.79	47.55	50.39	53.15
Honduras	8.1	4323.2	0.204	0.4157	533.3	568.8	603.2	645.1	684.9	725.8	765.6
Hungary*	9.95	-	-	0.5897	2916	3008	3127	3164	3271	3356	3439
Iceland*	0.33	-	-	0.00019	72.72	0.077	0.078	0.084	0.087	0.091	0.094
Indonesia	252	3620.7	0.18	0.6847	24125	25731	27287	29184	30984	32832	34632
India	1279	1452.2	0.095	1.333	1E+08	1E+08	1E+08	2E+08	2E+08	2E+08	2E+08
Iraq	33.77	15604	0.504	0.8206	10821	11540	12239	13089	13897	14726	15533
Ireland	4.63	52035	1.175	0.5212	2197	2343	2485	2658	2822	2990	3154
Israel*	7.73	-	-	0.7403	1619	1762	2504	2487	2738	2990	3242
Italy	60.99	35370	0.895	0.4109	17395	18553	19675	21043	22340	23673	24971
Jamaica	2.78	8305.3	0.323	0.7961	554.7	591.6	627.4	671	712.4	754.9	796.3
Japan	127.14	40455	0.984	0.4434	43005	45866	48641	52022	55230	58525	61733
Jordan	7.27	8305.1	0.323	0.6439	1173	1251	1327	1419	1507	1597	1684
Kazakhstan	16.44	23774	0.677	0.9232	7968	8498	9012	9638	10233	10843	11438
Kenya	44.35	2776.5	0.15	0.3323	1710	1824	1934	2068	2196	2327	2454
Kyrgyzstan	5.55	3229.3	0.166	0.0914	65.45	69.8	74.02	79.17	84.05	89.07	93.95
Latvia	2.05	15032	0.491	0.1921	149.8	159.8	169.4	181.2	192.4	203.8	215
Lebanon	4.82	14903	0.488	0.6948	1266	1350	1432	1532	1626	1723	1817
Libya	6.2	8282	0.323	0.9196	1426	1521	1613	1725	1832	1941	2047
Lithuania	3.02	15713	0.506	0.1159	137.3	146.5	155.3	166.1	176.4	186.9	197.2
Luxembourg*	0.53	-	-	0.276	183.6	186.1	180.2	201.8	211.5	221.1	230.8
Malawi	16.36	1099.2	0.078	0.7358	728.1	776.5	823.5	880.7	935	990.8	1045
Malaysia	29.72	24034	0.682	0.7488	11773	12556	13316	14241	15119	16021	16900
Maldives	0.35	13759	0.461	1.2138	151.8	161.9	171.7	183.7	195	206.6	218
Malta	0.43	23930	0.68	0.8661	196.4	209.5	222.2	237.6	252.3	267.3	282
Mauritania	3.89	3689.8	0.183	0.7358	405.6	432.5	458.7	490.6	520.9	551.9	582.2
Mauritius	1.24	18244	0.562	0.7358	397.6	424.1	449.7	481	510.7	541.1	570.8
Mexico*	122.33	-	-	0.4525	42913	45768	48537	51911	55112	58400	61601
Monaco	0.04	144200	1	0.0709	2.199	2.345	2.487	2.66	2.824	2.992	3.156
Mongolia	2.84	11094	0.396	2.3109	2016	2150	2280	2439	2589	2744	2894
Montenegro	0.62	7186.4	1	0.8225	395.3	421.6	447.1	478.2	507.7	538	567.5
Morocco	33.01	7239.9	0.294	0.7312	5493	5859	6213	6645	7055	7475	7885
Myanmar	53.26	4613.3	0.214	0.3157	2788	2973	3153	3372	3580	3794	4001
Namibia	2.3	9578.4	0.357	0.4898	312.1	332.9	353	377.6	400.9	424.8	448.1
Netherlands*	16.76	-	-	0.4133	5316	5413	5982	6412	6841	7271	7701
New Zealand	4.51	36169	0.91	0.1977	628.7	670.5	711.1	760.5	807.4	855.6	902.5
Nicaragua	6.08	4779.8	0.219	0.4721	487.9	520.3	551.8	590.2	626.6	663.9	700.3
Norway	5.08	102910	1.897	0.0022	16.44	17.53	18.59	19.88	21.11	22.37	23.59
Oman	3.63	43386	1.034	0.9365	2724	2905	3081	3295	3498	3707	3910
Pakistan	182.14	4619.7	0.214	0.4734	14309	15261	16184	17309	18376	19473	20540
Panama	3.86	19722	0.594	0.2768	491.9	524.6	556.3	595	631.7	669.4	706.1
Paraguay	6.8	8514.1	0.329	0	0	0	0	0	0	0	0
Philippines	98.39	6526.7	0.273	0.5267	10964	11694	12401	13263	14081	14921	15739
Poland*	38.22	-	-	1.1961	10361	12647	12790	14362	15577	16791	18006
Portugal	10.61	21618.7	0.633	0.4001	3291	3510	3722	3981	4227	4479	4724

Qatar	2.169	88305	1.703	0.5963	1708	1822	1932	2066	2194	2324	2452
Republic of Korea*	49.26	-	-	0.5044	5709	7068	7612	8427	8932	9621	10311
Rep. of Moldova	3.49	2244	0.129	0.6372	222.1	236.9	251.2	268.7	285.3	302.3	318.9
Romania	21.7	9585.3	0.358	1.0694	6433	6861	7276	7782	8262	8755	9234
Russian Federation	142.83	15544	0.502	0.5132	28544	30443	32284	34529	36658	38845	40974
Saudi Arabia	28.83	24934	0.7	0.7956	12452	13280	14084	15063	15992	16946	17874
Senegal	14.13	2272.5	0.13	0.5983	852	908.7	963.6	1031	1094	1159	1223
Sierra Leone	6.09	1712.8	0.107	0.7358	370.2	394.8	418.7	447.8	475.4	503.8	531.4
Singapore	5.41	56029	1.237	0.579	3004	3204	3398	3634	3858	4089	4313
Slovakia*	5.45	-	-	0.283	807.6	836.5	986	1092	1196	1299	1402
Slovenia*	2.07	-	-	0.5784	447.3	589.5	621.3	684.4	751.7	819	886.3
South Africa	52.78	12909	0.441	1.069	19281	20564	21808	23324	24763	26240	27678
Spain*	46.93	-	-	0.3439	15034	15892	16271	16969	17587	18205	18823
Sri Lanka	21.27	10596	0.384	0.4172	2640	2815	2985	3193	3390	3592	3789
Sudan	37.96	4323	0.204	0.615	3697	3943	4182	4473	4749	5032	5308
Suriname	0.54	15957	0.512	0.2097	44.92	47.91	50.8	54.33	57.69	61.13	64.48
Sweden	9.6	60283	1.303	0.023	223	237.8	252.2	269.7	286.3	303.4	320.1
Switzerland	8.08	84658.9	1.654	0.0032	20.04	21.38	22.67	24.25	25.74	27.28	28.77
Tajikistan	8.21	2525.7	0.14	0.00232	2.068	2.205	2.338	2.501	2.655	2.814	2.968
FYROM	2.11	5211.5	0.233	1.9406	739.6	788.8	836.5	894.7	949.8	1006	1062
Togo	6.82	1319.7	0.089	0.207	97.09	103.6	109.8	117.5	124.7	132.1	139.4
Trinidad and Tobago	1.34	33039	0.853	0.7667	679.8	725	768.8	822.3	873	925.1	975.8
Tunisia	11	10948	0.393	0.5722	1916	2043	2167	2317	2460	2607	2750
Turkey*	74.93	-	-	0.8657	80603	98650	1E+05	1E+05	1E+05	2E+05	2E+05
Uganda	37.58	1667	0.105	0.7358	2241	2390	2535	2711	2878	3050	3217
Ukraine	45.49	4029.7	0.194	0.3861	2648	2824	2995	3203	3400	3603	3801
United Kindgom	63.14	42407	1.017	0.5085	25318	27003	28636	30627	32515	34455	36344
United Rep. Tanzania	49.25	2397.2	0.135	0.2668	1375	1466	1555	1663	1766	1871	1974
USA*	320.05	-	-	0.5471	3E+05	3E+05	3E+05	3E+05	3E+05	3E+05	3E+05
Uruguay	3.41	19943	0.598	0.3037	480.5	512.5	543.5	581.2	617.1	653.9	689.7
Yemen	24.4	4007.8	0.194	0.6441	2360	2517	2669	2855	3031	3212	3388
Zambia	14.54	3701.4	0.183	0.0031	6.401	6.827	7.24	7.743	8.22	8.711	9.188
Zimbabwe	14.15	1997.1	0.119	0.6	781.3	833.3	883.7	945.2	1003	1063	1122
Sum (Gigatonnes)	6080				0.127	0.135	0.143	0.153	0.163	0.172	0.182

Table 6. Estimated carbon dioxide emissions for CT scanners in tonnes

Countries	Population 2013 ($\times 10^6$)	GDPC($) 2013	Ratio (Eq. 5)	EF_C Kg CO2/kWh	2010	2011	2012	2013	2014	2015	2016
Afghanistan	30.55	1877.4	0.114	1.2138	1965	2073	2123	2267	2364	2383	2525
Albania	3.17	4414.7	0.207	0.0091	3.037	3.204	3.28	3.503	3.653	3.683	3.901
Argentina	40.54	12977	0.442	0.3919	3973	4192	4292	4584	4780	4819	5105
Angola	21.47	6400.7	0.269	0.3795	1156	1219	1248	1333	1390	1401	1485
Armenia	2.98	7997.4	0.315	0.1282	64.79	68.35	69.98	74.75	77.94	78.57	83.24
Australia*	23.34	-	-	0.9918	15822	16693	17090	18254	19035	19189	20328
Austria	8.5	50504.7	1.15	0.1768	1027	1084	1109	1185	1236	1246	1320
Azerbaijan	9.41	17172	0.539	0.3918	1155	1218	1247	1332	1389	1400	1483
Bangladesh	157.6	951.9	0.071	0.6371	3085	3255	3332	3559	3712	3742	3964
Belarus	9.36	7978.8	0.314	0.6109	967.9	1021	1045	1117	1164	1174	1244
Belgium*	11.1	-	-	0.2248	1706	1799	1842	1968	2052	2068	2191
Belize	0.33	8179	0.32	0.2997	17.08	18.02	18.44	19.7	20.55	20.71	21.94
Bosnia & Herzegovina	3.83	5035.9	0.227	1.3262	594.3	627	641.9	685.6	714.9	720.7	763.5
Botswana	2.02	16111	0.515	1.8257	1097	1158	1185	1266	1320	1331	1410
Brazil	200.36	15968	0.512	0.0926	5481	5782	5920	6323	6594	6647	7042
Brunei Darussalam	0.42	81827	1.615	0.8195	377.4	398.1	407.6	435.4	454	457.7	484.8
Bulgaria	7.22	7674.9	0.306	1.166	1381	1457	1492	1594	1662	1675	1775
Burkina Faso	16.93	1616.8	0.102	0.7358	585.6	617.8	632.5	675.6	704.5	710.1	752.3
Cambodia	15.14	3069.3	0.161	1.1708	1394	1470	1505	1608	1677	1690	1791
Cameroon	22.25	3208.3	0.166	0.2166	392.7	414.3	424.1	453	472.4	476.2	504.5
Canada*	35.18	-	-	0.1798	4323	4561	4670	4988	5201	5243	5555
Chile*	17.62	-	-	0.4086	4921	5192	5315	5677	5920	5968	6322
China	1357	7077.8	0.289	0.9736	2E+05	2E+05	2E+05	2E+05	2E+05	2E+05	3E+05
Costa Rica	4.87	14513	0.479	0.0638	85.01	89.68	91.81	98.07	102.3	103.1	109.2
Côte d'Ivoire	20.32	2980.3	0.157	0.5112	797.7	841.6	861.6	920.3	959.7	967.4	1025
Croatia	4.29	13575	0.457	0.3865	429.9	453.6	464.4	496	517.3	521.4	552.4
Cuba	11.27	6760.2	0.28	0.9381	1567	1653	1692	1808	1885	1900	2013
Cyprus	1.14	27908	0.758	0.7717	406.8	429.2	439.4	469.3	489.4	493.4	522.6
Czech Republic*	10.7	-	-	0.9385	6864	7241	7414	7919	8258	8324	8818
Denmark*	5.62	-	-	0.3747	1439	1519	1555	1661	1732	1746	1849
Ecuador	15.74	11037	0.395	0.2696	932	983.3	1007	1075	1121	1130	1197
Egypt	82.06	10156	0.372	0.5001	8431	8895	9106	9727	10143	10225	10832
El Salvador	6.34	7902	0.312	0.2561	272.7	287.7	294.6	314.6	328.1	330.7	350.4
Eritrea	6.33	594	0.051	0.678	90.31	95.28	97.55	104.2	108.7	109.5	116
Estonia*	1.29	-	-	1.9069	1681	1774	1816	1940	2023	2039	2160
Ethiopia	94.1	1372	0.091	0.1189	461	486.4	497.9	531.9	554.6	559.1	592.3
Finland*	5.43	-	-	0.2255	836.9	883	904	965.6	1007	1015	1075
France*	64.29	-	-	0.0709	3116	3287	3365	3594	3748	3778	4003
Gabon	1.67	17078	0.537	0.4252	221.4	233.6	239.1	255.4	266.3	268.5	284.4
Gambia	1.85	1640	0.103	0.7358	64.72	68.28	69.91	74.67	77.86	78.49	83.15
Germany*	82.73	-	-	0.6722	38011	40102	41055	43854	45730	46099	48836
Greece*	11.13	-	-	1.9211	14615	15419	15785	16861	17583	17724	18777
Guyana	0.8	6931.4	0.285	0.2097	25.36	26.76	27.4	29.26	30.51	30.76	32.59

Honduras	8.1	4323.2	0.204	0.4157	348.5	367.7	376.4	402.1	419.3	422.7	447.8
Hungary*	9.95	-	-	0.5897	4010	4231	4332	4627	4825	4864	5153
Iceland*	0.33	-	-	0.00019	0.043	0.045	0.046	0.049	0.052	0.052	0.055
Indonesia	252	3620.7	0.18	0.6847	15491	16343	16731	17872	18636	18787	19902
India	1279	1452.2	0.095	1.333	7E+07	8E+07	8E+07	8E+07	9E+07	9E+07	9E+07
Iraq	33.77	15604	0.504	0.8206	8036	8478	8680	9271	9668	9746	10324
Ireland	4.63	52035	1.175	0.5212	1840	1941	1987	2123	2213	2231	2364
Israel*	7.73	-	-	0.7403	3911	4127	4225	4513	4706	4744	5025
Italy	60.99	35370	0.895	0.4109	14016	14787	15138	16170	16862	16998	18007
Jamaica	2.78	8305.3	0.323	0.7961	386.9	408.2	417.9	446.3	465.4	469.2	497.1
Japan	127.14	40455	0.984	0.4434	35116	37048	37929	40515	42248	42589	45117
Jordan	7.27	8305.1	0.323	0.6439	818.3	863.3	883.8	944.1	984.4	992.4	1051
Kazakhstan	16.44	23774	0.677	0.9232	6171	6510	6665	7119	7424	7484	7928
Kenya	44.35	2776.5	0.15	0.3323	1069	1128	1155	1234	1286	1297	1374
Kyrgyzstan	5.55	3229.3	0.166	0.0914	41.55	43.83	44.87	47.93	49.98	50.39	53.38
Latvia	2.05	15032	0.491	0.1921	110.8	116.9	119.7	127.9	133.3	134.4	142.4
Lebanon	4.82	14903	0.488	0.6948	936	987.4	1011	1080	1126	1135	1203
Libya	6.2	8282	0.323	0.9196	994.4	1049	1074	1147	1196	1206	1278
Lithuania	3.02	15713	0.506	0.1159	102.1	107.7	110.2	117.8	122.8	123.8	131.1
Luxembourg*	0.53	-	-	0.276	99.98	105.5	108	115.4	120.3	121.3	128.5
Malawi	16.36	1099.2	0.078	0.7358	415.1	438	448.4	479	499.4	503.5	533.4
Malaysia	29.72	24034	0.682	0.7488	9127	9630	9858	10530	10981	11070	11727
Maldives	0.35	13759	0.461	1.2138	111.4	117.5	120.3	128.5	134	135.1	143.1
Malta	0.43	23930	0.68	0.8661	152.2	160.6	164.4	175.6	183.1	184.6	195.6
Mauritania	3.89	3689.8	0.183	0.7358	260.9	275.2	281.8	301	313.9	316.4	335.2
Mauritius	1.24	18244	0.562	0.7358	299.9	316.4	324	346	360.8	363.8	385.4
Mexico*	122.33	-	-	0.4525	11500	12133	12421	13268	13835	13947	14775
Monaco	0.04	144200	1	0.0709	1.938	2.045	2.094	2.236	2.332	2.351	2.49
Mongolia	2.84	11094	0.396	2.3109	1447	1527	1563	1670	1741	1755	1860
Montenegro	0.62	7186.4	1	0.8225	79.37	83.73	85.73	91.57	95.49	96.26	102
Morocco	33.01	7239.9	0.294	0.7312	3779	3987	4082	4360	4546	4583	4855
Myanmar	53.26	4613.3	0.214	0.3157	1834	1934	1980	2115	2206	2224	2356
Namibia	2.3	9578.4	0.357	0.4898	220.8	233	238.5	254.8	265.6	267.8	283.7
Netherlands*	16.76	-	-	0.4133	4735	4995	5114	5462	5696	5742	6083
New Zealand	4.51	36169	0.91	0.1977	507.7	535.6	548.3	585.7	610.8	615.7	652.3
Nicaragua	6.08	4779.8	0.219	0.4721	322	339.8	347.8	371.5	387.4	390.6	413.8
Norway	5.08	102910	1.897	0.0022	14.73	15.54	15.91	16.99	17.72	17.86	18.92
Oman	3.63	43386	1.034	0.9365	2240	2363	2419	2584	2695	2717	2878
Pakistan	182.14	4619.7	0.214	0.4734	9413	9931	10167	10860	11325	11416	12094
Panama	3.86	19722	0.594	0.2768	373.9	394.5	403.9	431.4	449.8	453.5	480.4
Paraguay	6.8	8514.1	0.329	0	0	0	0	0	0	0	0
Philippines	98.39	6526.7	0.273	0.5267	7466	7876	8064	8613	8982	9054	9592
Poland*	38.22	-	-	1.1961	31247	32966	33749	36050	37592	37895	40145
Portugal	10.61	21618.7	0.633	0.4001	2902	3061	3134	3348	3491	3519	3728
Qatar	2.169	88305	1.703	0.5963	1507	1590	1628	1739	1814	1828	1937

Republic of Korea*	49.26	-	-	0.5044	16983	17917	18343	19594	20432	20597	21820
Republic of Moldova	3.49	2244	0.129	0.6372	136	143.5	146.9	156.9	163.6	164.9	174.7
Romania	21.7	9585.3	0.358	1.0694	4551	4802	4916	5251	5475	5520	5847
Russian Federation	142.83	15544	0.502	0.5132	21190	22356	22887	24447	25493	25699	27225
Saudi Arabia	28.83	24934	0.7	0.7956	9689	10222	10465	11179	11657	11751	12449
Senegal	14.13	2272.5	0.13	0.5983	522.2	551	564.1	602.5	628.3	633.4	671
Sierra Leone	6.09	1712.8	0.107	0.7358	220.6	232.8	238.3	254.5	265.4	267.6	283.4
Singapore	5.41	56029	1.237	0.579	2534	2674	2737	2924	3049	3073	3256
Slovakia*	5.45	-	-	0.283	1054	1112	1139	1216	1268	1279	1354
Slovenia*	2.07	-	-	0.5784	818.4	863.4	883.9	944.2	984.5	992.5	1051
South Africa	52.78	12909	0.441	1.069	14051	14824	15177	16211	16905	17041	18053
Spain*	46.93	-	-	0.3439	11031	11638	11915	12727	13271	13379	14173
Sri Lanka	21.27	10596	0.384	0.4172	1886	1990	2037	2176	2269	2287	2423
Sudan	37.96	4323	0.204	0.615	2416	2549	2610	2788	2907	2931	3105
Suriname	0.54	15957	0.512	0.2097	33.43	35.27	36.11	38.57	40.22	40.55	42.95
Sweden	9.6	60283	1.303	0.023	189.4	199.9	204.6	218.6	227.9	229.7	243.4
Switzerland	8.08	84658.9	1.654	0.0032	17.67	18.65	19.09	20.39	21.26	21.43	22.71
Tajikistan	8.21	2525.7	0.14	0.00232	1.281	1.351	1.383	1.478	1.541	1.553	1.645
FYROM	2.11	5211.5	0.233	1.9406	492.4	519.5	531.9	568.1	592.4	597.2	632.7
Togo	6.82	1319.7	0.089	0.207	56.38	59.48	60.9	65.05	67.83	68.38	72.44
Trinidad and Tobago	1.34	33039	0.853	0.7667	544	573.9	587.6	627.6	654.4	659.7	698.9
Tunisia	11	10948	0.393	0.5722	1373	1449	1483	1584	1652	1666	1764
Turkey*	74.93	-	-	0.8657	44337	46776	47888	51153	53341	53771	56964
Uganda	37.58	1667	0.105	0.7358	1332	1405	1439	1537	1603	1615	1711
Ukraine	45.49	4029.7	0.194	0.3861	1718	1813	1856	1982	2067	2084	2208
United Kindgom	63.14	42407	1.017	0.5085	20771	21914	22435	23964	24989	25191	26687
United Rep. Tanzania	49.25	2397.2	0.135	0.2668	847.3	893.9	915.1	977.5	1019	1028	1089
USA*	320.05	-	-	0.5471	1E+05	1E+05	1E+05	1E+05	1E+05	1E+05	2E+05
Uruguay	3.41	19943	0.598	0.3037	365.7	385.8	395	421.9	439.9	443.5	469.8
Yemen	24.4	4007.8	0.194	0.6441	1531	1615	1653	1766	1842	1857	1967
Zambia	14.54	3701.4	0.183	0.0031	4.119	4.345	4.449	4.752	4.955	4.995	5.292
Zimbabwe	14.15	1997.1	0.119	0.6	472.8	498.8	510.7	545.5	568.8	573.4	607.5
Sum (Gigatonnes)	6080				0.074	0.078	0.08	0.086	0.089	0.09	0.095