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Projected long-term behavior of the CO_2 emission factor in the electricity system of Uruguay

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Abstract: Estimating CO_2 emission factor of the electricity system is a key aspect in the calculation of the baseline emissions for projects certified as Clean Development Mechanism (CDM), which replace energy from the grid. Uruguay is currently driving the expansion of the electricity system based on domestic renewable energies, in addition to replacing oil-based fuels for others with lower emission factors. This implies a substantial change of the generation park in the next decade and of the associated CO_2 emissions. In this paper a calculation methodology of the baseline emissions is adapted for its incorporation in the software SimSEE (Electric Energy Systems Simulator), which is used for modeling the Uruguayan electric system, and therefore allows modeling the current energy generator park and the future one. Using this tool, the CO_2 emission factor's evolution is evaluated in the 2012-2020 period. The 2020 scenario is based on an optimal expansion of the electric system. The results indicate a strong reduction of the emission factor between 2012 and 2020, going from average values (for 100 simulations) around 0.60 tCO_2/MWh to 0.15 tCO_2/MWh. In this possible future scenario, CDM certification will probably not act as a strong incentive in Uruguay for the development of projects based on non-traditional renewable energies.

Key words: carbon emissions, electric system, clean development mechanism, future energy scenario.

1. Introduction

The estimation of the CO_2 emission factor of the electric system is a key aspect in the calculation of the baseline emissions for projects certified as Clean Development Mechanism (CDM), which replace energy from the grid. That is, for CDM projects that supply electricity to the grid or that result in electricity savings which would have been provided by the grid, for example, renewable energy generation projects, or efficiency energy projects.

On the other hand, Uruguay is currently driving the expansion of the electric energy generation system mainly based on domestic renewable energies, such as wind, mini hydro and solar energy. In addition, natural gas is also being incorporated to the energy matrix, which will replace in practice the use of oil based fuels such as gasoil and fuel oil, taking them to reduced levels. The latter implies a substantial change of the energy generation park in the next decade and of the associated CO_2 emissions.

Therefore, one of the objectives of this paper is to adapt a calculation methodology of the baseline emissions for its incorporation in the software SimSEE – Electric Energy Systems Simulator [1] (iie.fing.edu.uy/simsee).

SimSEE software is used for the electric system modeling, so it allows modeling both the current energy generator park and the one projected for the future. Thus, the second objective of this paper is to calculate the CO_2 emission factor in two different scenarios of the electric system: the current scenario

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(year 2012) and a future scenario, for the year 2020. By comparing the results obtained it is possible to evaluate the incentives for the CMD projects' certification in our country.

2. Background

The United Nations Framework Convention on Climate Change (UNFCCC) has among its members almost all countries of the world, and is the Treaty which serves as base for the Kyoto Protocol of 1997. In the context of the Protocol, whose first commitment period came into force in 2005, 37 States – Industrialized States or in process of transition to a market economy – have legally binding commitments of emissions limitation and reduction. The ultimate objective of both treaties is to stabilize the GHG concentrations in the atmosphere placing them in a level which prevents dangerous human interference in the climatic system.

The first step towards complying with the Kyoto Protocol expired in late 2012. In December of this same year it was agreed at the Climate Change Conference held in Doha, Qatar, a second period for compliance with the Kyoto Protocol from 2013 to 2020. However, in this second period various countries retire from the compromise of limiting the emissions: Japan, Canada, New Zeeland and Russia. This way, the only countries left with obligations are the European Union, Australia, Norway, Iceland, Croatia, Kazakhstan, Liechtenstein and Monaco [2].

The CDM is one of the flexibility mechanisms of the Kyoto Protocol, designed to facilitate the compliance with the greenhouse gases (GHG) emission reduction commitments for industrialized countries. It is supervised by the CDM Executive Board (EB) and it is under the guidance of the Conference of the UNFCCC Parties.

Under the CDM, the projects which demonstrate they cause a net reduction of emissions with respect to a reference scenario (situation without project) in developing countries, they can get negotiable credits to compensate emissions, known as Certified Emission Reductions (CERs for its acronym in English). Each of these CERs is the equivalent to 1 ton of carbon dioxide. Countries with a commitment to reduce or limit emissions under the framework of the Kyoto Protocol can use CERs to meet a part of their obligations under the Protocol [3].

To estimate GHG emission reductions of a certain project, it is necessary to follow these steps:

- Estimation of the base line emissions using a selected methodology.
- Estimation of the emission of the project to be certified as CDM.
- Estimation of the GHG emission reduction due to the project implementation.

For the purpose of this work the interest is focused on adapting a base line emission calculation methodology for the Uruguayan electric system for general use, independently of the project which is desired to register as CDM.

The base line methodology describes the steps which must be taken into account to identify the most likely scenario in the absence of the CDM project, in order to calculate the emissions associated with this scenario, and the emission reduction which the project implies. This methodology must be previously approved by the EB of the CMD.

In the case of Uruguay, one of the approved methodologies consists on the combination of two emission factors, the Operating Margin Emission Factor (OM for its acronym in English) and the Build Margin Emission Factor (BM for its acronym in English), in accordance with the procedure described in the "Tool to calculate the emission factor for an electricity system" [4] of the UNFCCC. The Operating Margin Emission Factor allows estimating the emission factor of the generator which would have operated instead of the proposed CDM project. The Build Margin Emission Factor allows estimating the emission factor which would have been built instead of the CDM proposed project. This procedure has already been used for the emissions calculation in the Uruguayan electric system by UTE [5] and by many emission reduction projects approved by the Climate Change Unit of the National Environment Direction, certified or in process of certification as CDM [6].

3. Methodology

The proposed methodology to calculate the emission factor of CO_2 is based in the following document: "Tool to calculate the emission factor for an electricity system" [4]. This work does not intend to supersede the procedure described in that document, but rather to adapt the methodology for its application in the SimSEE. This adaptation is meant to be used in the calculation of the Uruguayan electricity system emissions.

The base document proposes the use of historic data to perform the computations. The incorporation of the methodology to the SimSEE allows the calculation of the emission factor for future years, based in simulations of the electricity system operation with an optimal operation policy. Thus, future aspects such as an increase in energy demand or the incorporation of new generation units/plants can be taken into account in the calculations.

The SimSEE is a model that optimizes and simulates the operation of an electric system and has been widely used to analyze short term dispatch and long term planning of the integrated power system in Uruguay [7], [8] and [9]. It uses stochastic dynamic optimization to find an operation policy that minimizes the expected value of the cost of future operation, while the simulations compute the detailed operation of multiple realizations -called chronicles- of the involved stochastic processes over the analyzed period of time using the optimal operation policy. SimSEE needs to represent those stochastic processes that characterize the uncertainty faced by the system. One of these processes is the streamflow to hydroelectric dams, which is characterized in both optimization and simulation phases by a stochastic generator CEGH (Spanish acronym for "Correlation in Gaussian space with histogram), which is calibrated using approximately 100 years of historic streamflow data. It is out of the scope of this work to thoroughly describe the CEGH, more information can be found in [10]. Another source of uncertainty is the availability of generators in each time step, represented by an availability coefficient, which can be based in historic data or estimated for new power plants. Other variables, such as the price of oil, can also be represented by a stochastic process depending on its value in previous time step and a random component calibrated with historic data.

These uncertainties lead to different possible operations of the electricity system. This variability is represented by the number of simulation chronicles. The annual emission factor of CO_2 is different for each chronicle. Therefore, for each year of the simulation period, instead of having a single value of the emission factor, the range and distribution of its values is obtained.

Based on the "Tool to calculate the emission factor for an electricity system" [4], the emission factor of CO_2 is determined through the calculation of the "combined margin" emission factor (CM), named $EF_{grid,CM,y}$, in tons of CO_2 per MWh of energy produced in year "y". CM is a result of the weighted average of two other factors of the electricity system: **1)** the OM, and **2)** the BM. The OM ($EF_{grid,OM,y}$) is the emission factor that refers to the group of existing power plants whose current electricity generation would be affected by the proposed project or activity. The BM ($EF_{grid,BM,y}$) is the emission factor that refers to the group of prospective power plants whose construction and future operation would be affected by the proposed project or activity.

1) Three calculation procedures to estimate the OM emission factor ($EF_{grid,OM,y}$) are incorporated to the SimSEE: simple OM ($EF_{grid,OMsimple,y}$), simple adjusted OM ($EF_{grid,OM-adj,y}$), and average OM ($EF_{grid,OM-ave,y}$). The base document also presents a fourth method to calculate the OM factor using dispatch data analysis. This method can be applied to a specific CDM project. Given that the aim of this work is to evaluate the evolution of the baseline emissions, independently of the type of project or activity to be incorporated to the electricity system, the fourth method is not considered.

The **simple OM** emission factor can be estimated from (1) as the generation-weighted average CO_2 emission per unit net electricity generation (tCO_2/MWh) of all generating power plants serving the system, not including low-cost/must-run (LCMR) power plants. LCMR resources are defined as power plants with low marginal generation costs or dispatched independently of the daily or seasonal load of the grid. They typically include: hydro, geothermal, wind, low-cost biomass, nuclear and solar generation. Otherwise, the generators are called high-cost/may-run (HCMR). The simple OM emission factor can only be used if LCMR resources constitute less than 50% of the total generation in the system.

$$EF_{grid,OMsimple,y} = \frac{\sum_m \left(EG_{m,y} \times EF_{EL,m,y}\right)}{\sum_m EG_{m,y}} \quad (1)$$

Where:

$EF_{grid,OMsimple,y}$ = simple OM CO_2 emission factor in year "y" (in tCO_2/MWh).

$EG_{m,y}$ = net quantity of energy generated and delivered to the grid by power unit "m" in year "y" (in MWh).

$EF_{EL,m,y}$ = CO_2 emission factor of power unit "m" in year "y" (intCO_2/MWh).

m = all power units serving the grid in year "y", except LCMR power units.

For each simulation chronicle, SimSEE annually accumulates the electricity generated by each power unit ($EG_{m,y}$). From $EG_{m,y}$ and $EF_{EL,m,y}$ (input by the user), it calculates $EF_{grid,OMsimple,y}$ for each year "y" of the simulation period, considering only LCMR power units.

Simple adjusted OM factor is a variation of simple OM, which considers separately LCMR (k) and HCMR (m) generators (including imports). Similarly to simple OM, it is calculated based on the net energy generation of each power unit and its emission factor, according to (2).

$$EF_{grid,OM-adj,y} = (1-\lambda_y) \times \frac{\sum_m \left(EG_{m,y} \times EF_{EL,m,y}\right)}{\sum_m EG_{m,y}} + \lambda_y \times \frac{\sum_k \left(EG_{k,y} \times EF_{EL,k,y}\right)}{\sum_k EG_{k,y}} \quad (2)$$

Where:

$EF_{grid,OM-adj,y}$ = simple adjusted OM CO_2 emission factor in year "y" (in tCO_2/MWh).

λ_y = (lambda) factor expressing the percentage of time when LCMR power units are on the margin in year "y".

$EG_{m,y}$ = net quantity of electricity generated and delivered to the grid by power unit "m" in year "y" (in MWh).

$EG_{k,y}$ = quantity of electricity generated and delivered to the grid by power unit "k" in year "y" (in MWh).

$EF_{EL,m,y}$ = CO_2 emission factor of power unit "m" in year "y" (intCO_2/MWh).

$EF_{EL,k,y}$ = CO_2 emission factor of power unit "k" in year "y" (intCO_2/MWh).

m = all power units serving the grid in year "y", except LCMR power units.

k = all LCMR power units serving the grid in year "y".

For each simulation chronicle, SimSEE annually accumulates the net energy generated by each power unit ($EG_{m,y}$, $EG_{k,y}$). From these, λ_y, $EF_{EL,m,y}$, and $EF_{EL,k,y}$ (inputs by the user) it calculates $EF_{grid,OM-adj,y}$ for each year "y" of the simulation period, considering all generators LCMR and HCMR.

The parameter λ_y is defined as:

$$\lambda_y = \frac{\text{Number of hours LCMR are on the margin in year "y"}}{\text{Total number of hours in the year}} \quad (3)$$

To calculate λ_y from (3) it is necessary to know the hourly load duration curve for each year "y". SimSEE allows the division of the time step into blocks, which is used to estimate the load duration curve. The number of blocks and their duration is defined by the user. For each time step (typically weekly when the simulation period is one or more years), the demanded load is sorted into the defined blocks, so that the hours of higher load are grouped in block 1, then block 2 and so on. Each block is represented by the average load of the hours grouped in it. The larger number of blocks, the better the estimated curve represents the hourly load duration curve.

For each year and simulation chronicle, the load associated to each block is decreasingly sorted and plotted against the hours of the year. All the hours in a given block have the same load value, which is the average load of the hours grouped in the block, as explained in the previous paragraph. Fig. 1 (step 1) shows an example of the estimated load duration curve estimated in the SimSEE.

To estimate the hours LCMR sources are on the margin, firstly the annual LCMR generation (in MWh) must be calculated. Next, the load duration curve should be filled with this generation. Graphically, it can be represented as a horizontal line that intersects the load duration curve so that the area below the curve equals the total LCMR generation (step 2 in Fig. 1). The amount of hours to the right of the intersection is the number of hours LCMR resources are on the margin (steps 3 and 4 on Fig. 1). If the horizontal line and the load duration curve do not intersect, it can be concluded that LCMR sources do not appear on the margin and λ_y is equal to zero.

Average OM emission factor is calculated as the average emission rate of all power plants serving the grid. The same methodology explained above for the simple OM can be used, but including LCMR power plants in (1).

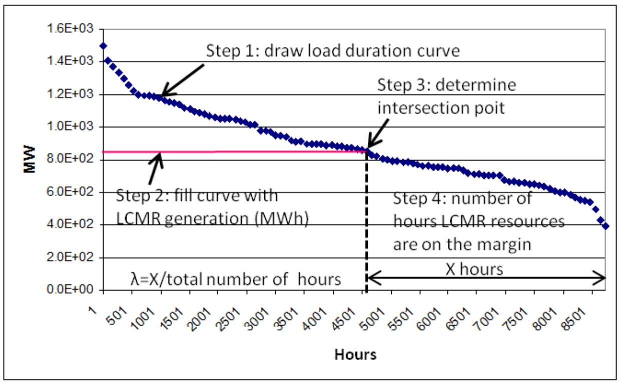

Fig. 1 Example of load duration curve for a year y and a given chronicle (represented by 100 values). The steps to calculate factor λ are graphically indicated.

2) To estimate the BM emission factor it is necessary to consider, following a specific procedure and excluding power units registered as CDM, the set of power plants that started to supply electricity to the grid most recently and that comprise at least 20% of the annual energy generation. BM emission factor can be computed for each year *y* of the simulation period as the generation-weighted average emission factor (tCO_2/MWh) of the selected set of power plants, using (4).

$$EF_{grid,BM,y} = \frac{\sum_n \left(EG_{n,y} \times EF_{EL,n,y}\right)}{\sum_n EG_{n,y}} \quad (4)$$

Where:

$EF_{grid,BM,y}$ = BM CO_2 emission factor in year "y" (in tCO_2/MWh).

$EG_{n,y}$ = net quantity of electricity generated and delivered to the grid by power unit "n" in year "y" (in MWh).

$EF_{EL,n,y}$ = CO_2 emission factor of power unit "n" in year "y" (intCO_2/MWh).

n = all power units serving the grid, which are included in the set of power units used to calculate BM in year "y".

SimSEE accumulates, for each simulation chronicle, the net annual energy that each power unit supplies to the grid ($EG_{n,y}$). From $EG_{n,y}$ and $EF_{EL,n,y}$ (input by the user) it calculates $EF_{grid,BM,y}$ for each year *y* of the simulation period, and for each simulation chronicle. Units *n* are the set of power plants that started to supply electricity to the grid most recently, excluding projects registered as CDM, and that comprise at least 20% of the annual energy generation. A detailed procedure on how these power units are selected can be found in [4].

Finally, the combined margin (CM) emission factor ($EF_{grid,CM,y}$) is calculated as a weighted average of OM and BM factors, for each year *y* and each simulation chronicle, as in (5).

$$EF_{grid,CM,y} = EF_{grid,OM,y} \times w_{OM} + EF_{grid,BM,y} \times w_{BM} \quad (5)$$

Where w_{OM} and w_{BM} are the weights that multiply OM and BM emission factors, respectively. They depend on the type of CDM project that the user is evaluating:

- For solar and wind power plants w_{OM}=0.75 and w_{BM}=0.25.
- For other type of generators w_{OM}=0.50 and w_{BM}=0.50.

These weights are proposed by [4] for the first crediting period of the CDM project under consideration.

To summarize, by incorporating the precedent calculation procedure to the SimSEE, it is possible to obtain the OM, BM and CM emission factors of the electric system for each year of the simulation period. Due to uncertainties, there are several possible ways to operate the system, which are represented by the number of simulation chronicles. For each chronicle, the calculated annual emission factor is different. Therefore, for each year, we have the distribution of the emission factor and its potential range of variation.

4. Scenarios of the electricity system

Two different scenarios of the Uruguayan electric system were modeled in SimSEE: current (2012) and the year 2020. The 2012 scenario is based on the one developed and used by the administration for energy planning. The characteristics of this system are available in [11], including the availability coefficients for generators. The 2020 scenario is based on an optimal expansion of the electric generation in Uruguay [7]. It is important to highlight that this is a hypothetical possible scenario for the year 2020, which is consistent with UTE's guidelines to drive the expansion of renewable energies and the use of natural gas to replace oil based fuels. In this scenario the availability coefficient for new power plants was assumed 0.85 for thermal generators, 0.80 for biomass generators, and 0.98 for wind farms. In both scenarios streamflow was modeled as a stochastic process calibrated with approximately 100 years of historic records. Hence, historic inter-annual variability is represented by the model.

The main differences between 2012 and 2020 scenarios are:

- Bigger energy demand in the year 2020. In addition to the vegetative growth of energy demand, an important industrial development is projected in the following years, which involves moving from a demand of 10154 GWh in the year 2012 to a demand of 16192 GWh in the year 2020.
- For the year 2020 a 48 MW steam turbine which operates with heavy fuel oil will no longer be used in the thermoelectric power plant "José Batlle y Ordóñez".
- In the year 2015 a 540 MW combined cycle power plant which will consume natural gas will be incorporated to the system. In addition, it is planned for approximately 300 MW of turbines which operate with gas oil at the thermoelectric power plant "Punta del Tigre", change to natural gas.
- In the year 2014 the interconnection of the Uruguayan electric system with Brazil will increase in 500 MW. When incorporating the interconnection in SimSEE, a high level of electric integration and exchange between the countries is considered, based on the work of [8].

- By the year 2015, 1200 MW of additional wind generation are planned in the electric system with respect to the year 2012. For 2020, 1800 MW of additional wind generation are planned with respect to the year 2012.
- By the year 2015, 200 MW of additional biomass generation are planned in the electric system with respect to the year 2012.

The simulation period goes from 01/01/2012 to 31/12/2020. As it has been previously mentioned, an important demand development is projected, and wind, biomass and natural gas generation are incorporated. Table 1 summarizes the different generators which are incorporated, the year when they are incorporated to the electric system, their emission factor, and their classification as LCMR or HCMR and as CDM or not CDM.

The emission factor of each generator must be calculated by the user, and incorporated as an input data to the SimSEE. For a unit *m* (or *k*) for which energy generation data and its fuel type are known, the emission factor is calculated based on the fuel's CO_2 emission factor and the unit's efficiency factor, according to:

$$EF_{EL,m,y} = \frac{EF_{CO2,m,i,y} \times 3.6}{\eta_{m,y}} \qquad (6)$$

Where:

$EF_{EL,m,y}$ = CO_2 emission factor of power unit *m* in the year *y* (tCO_2/MWh).

$EF_{CO2,m,i,y}$= Average CO_2 emission factor for fuel type *i*, used in unit *m* in the year *y* (tCO_2/GJ).

$\eta_{m,y}$ = Average net energy conversion efficiency of power unit *m* in year *y* (rate).

For hydro, wind and biomass generators the emission factor is assumed to be zero.

For thermoelectric generators, the emissions factors were calculated, when possible, based on [12]. For those generators which have not yet been incorporated to the electric system, as it is the case of the natural gas combined cycle power plant, (CC470_GN, see Table 1) and the gasoil turbines of the thermoelectric power plant “Punta del Tigre” when they start consuming natural gas (PTI_GN, see Table 1), estimated emission factors were considered according to [13].

To perform the SimSEE simulation, the number of blocks and hours per block were left as configured by default as: 4 blocks of 7, 28, 91 and 42 hours, respectively. The number of chronics for the simulation is 100.

5. Results

Using the tool to calculate CO_2 emissions that was incorporated to the SimSEE, OM, BM and CM emission factors are estimated for the years 2012 and 2020. 100 simulation chronicles are used. Each chronicle uses the same optimal operation policy, found during the optimization phase, but the results –the energy dispatch, which directly affects the emissions- is different because SimSEE models both stochastic and random processes, and the random components produce a different dispatch in each simulation. Therefore, the group of chronicles can be seen as the result of Monte Carlo simulations based on the statistical models used by the SimSEE, which represent the availability of generators and the streamflow inputs to hydroelectric dams. A dominant feature of streamflow time series is that they show very high interannual variability, which represents a major uncertainty for energy planning in Uruguay [7]. Hence, it is expected that the results will also present a high variability.100 chronicles is found to be a reasonable trade-off between reducing computational time and capturing this variability.

Thus, for each year, the distribution of the emission factors is obtained. They are analyzed through statistic indicators as the mean, median and standard deviation. A summary of the results for the year 2012 is presented in Table 2, while Table 3 shows the results for 2020.

Table 1 Uruguayan electric system's generators summary.

Name	Description	Year of incorporation to the system	EF (tCO_2/MWh)	LCMR/ HCMR	CDM
Bonete	Hydroelectric generator with reservoir. Maximum generating power: 155.2 MW.	1946	0	✓	
SalaB_FO	Thermoelectric generator which uses fuel oil. Maximum power: 48 MW.	1955 (out of service from 2015)	0.894		
Baygorria	Run of the river hydroelectric generator. Maximum generating power: 108 MW.	1960	0	✓	
CB-5ta-FOP	Thermoelectric generator which uses fuel oil. Maximum power: 75 MW.	1970	0.838		
CB-6ta-FOP	Thermoelectric generator which uses fuel oil. Maximum power: 120 MW.	1975	0.860		
SG	Run of the river hydroelectric generator. "Salto Grande". Maximum generating power: 945 MW.	1979	0	✓	
Palmar	Run of the river hydroelectric generator. Maximum generating power: 333 MW.	1982	0	✓	
CTR_GO	Thermoelectric generator which uses gasoil. Maximum power: 200 MW.	1991	0.940		
PTI_GO	Thermoelectric generator which uses gasoil. Maximum power: 294 MW. In 2014 start operating with natural gas (PTI_GN).	2006 (from 2014 start operating with natural gas).	0.713		
eolico_L0	Wind farm. Maximum wind turbine power: 1.95 MW each. From 2008 to 2013 increase from 7 to 38 generating units.	2008 – 7 units incorporated 2010 – 6 units incorporated 2011 – 8 units incorporated 2013 – 17 units incorporated	0	✓	✓
Gdis80	Represents the distributed wind and biomass generation. Maximum power: 32 MW in 2009 and 128 MW in 2011.	2009 –32 MW incorporated 2011 –96 MW incorporated	0	✓	✓
Motores	Thermoelectric generator which uses fuel oil. Maximum power: 80 MW.	2009	0.610		
Biomasa Convocable	Thermoelectric generator which uses biomass as fuel. Maximum power: 10 MW in 2013 and 20 MW in 2014.	2013 – 10 MW incorporated 2014 – 10 MW incoporated	0		✓
eolico_L1	Wind farm. Maximum wind turbine power: 1.95 MW each. From 2013 to 2014 increase from 25 to 75 generating units.	2013 – 25 units incorporated 2014 –50 units incorporated	0	✓	✓
eolico_L2	Wind farm. Maximum wind turbine power: 1.95 MW each. From 2013 to 2014 increase from 25 to 95 generating units.	2013 – 25 units incorporated 2014 – 70 units incorporated	0	✓	✓
eolico	Wind farm. Maximum wind turbine power: 1.95 MW each. From 2013 to 2020 increase from 100 to 732 generating units.	2013 – 100 units incorporated 2014 – 220 units incorporated 2015 – 70 units incorporated 2016 – 30 units incorporated 2018 – 100 units incorporated 2019 – 60 units incorporated	0	✓	✓

Name	Description	Year of incorporation to the system	EF (tCO_2/MWh)	LCMR/ HCMR	CDM
		2020 – 152 units incorporated			
Biomasa Auto Despachada	Thermoelectric generator which uses biomass as fuel. Maximum power: 90 MW in 2013 and 180 MW in 2014.	2013 – 90 MW incorporated 2014 – 90 MW incorporated	0	✓	✓
CC470_GN	Thermoelectric generator which uses natural gas as fuel. Maximum power: 360 MW in 2014 and 540 MW in 2015.	2014 – 360 MW incorporated 2015 – 180 MW incorporated	0.400		
PTI_GN	Thermoelectric generator which uses natural gas as fuel. Maximum power: 294 MW.	2014	0.630		

Table 2 Summary of emission factors results for 100 simulation chronicles, year 2012. Columns 6 and 7 show the values of the CM emission factor. In both cases simple-adjusted OM was used to calculate CM. Weights wOM = 0.75 and wBM = 0.25 were used for results in column 6 (recommended for solar or wind power projects), while wOM = 0.50 and wBM = 0.50 were used for results in column 7 (recommended for CDM projects other than wind or solar).

	Average OM	Simple OM	Simple-adjusted OM	BM	CM (Simp-adjust. OM, solar or wind power)	CM (Simp-adjust. OM, other than solar or wind power)
Mean	0.199	0.763	0.665	0.391	0.597	0.528
Median	0.192	0.762	0.670	0.496	0.621	0.582
Mode*	0.110	0.750	0.778	0.531	0.723	0.669
St. Dev.	0.096	0.012	0.112	0.175	0.125	0.141
Min	0.045	0.733	0.392	0.073	0.314	0.236
Max	0.434	0.791	0.791	0.582	0.737	0.684
Range	0.389	0.058	0.399	0.509	0.423	0.448

*****By dividing the range into 15 equal bins, the mode is calculated as the average value of the most frequent bin (i.e. with the greater number of elements).

Table 3 Same as Table 2 but for year 2020.

	Average OM	Simple OM	Simple-adjusted OM	BM	CM (Simp-adjust. OM, solar or wind power)	CM (Simp-adjust. OM, other than solar or wind power)
Mean	0.030	0.371	0.178	0.121	0.164	0.150
Median	0.017	0.367	0.148	0.082	0.130	0.113
Mode*	0.006	0.364	0.041	0.019	0.037	0.030
St. Dev.	0.032	0.042	0.117	0.105	0.114	0.111
Min	0.001	0.276	0.028	0.007	0.023	0.018
Max	0.124	0.480	0.401	0.337	0.385	0.369
Range	0.122	0.204	0.373	0.330	0.362	0.351

*****By dividing the range into 15 equal bins, the mode is calculated as the average value of the most frequent bin (i.e. with the greater number of elements).

As explained in the Methodology Section, simple OM factor calculation procedure does not consider the energy delivered by LCMR unit powers. It can be observed from Tables 2 and 3 that simple OM results have higher mean, median, and mode than the values obtained using average OM and simple-adjusted OM methods. It also presents lower standard deviation and range than this latter methods in 2012 (Table 2) and than simple-adjusted OM in 2020 (Table 3). These results can mislead to interpret that simple OM is a robust and convenient method to estimate baseline emissions for a project activity that substitutes grid electricity.

However, according to [4], the simple OM method can only be used if LCMR resources comprise less than 50% of the net energy generation based on: i) the average of the 5 most recent years; or ii) long-term average of the hydroelectric generation. In Uruguay, between 2007 and 2011, LCMR power units account for 65% of the net energy production [14]. Thus, the simple OM methodology cannot be used in 2012.

To determine if the simple OM method can be used in 2020 we calculate, for each chronicle simulated between 2015 and 2019, the percentage of the total energy supplied to the grid by LCMR resources. For all years and chronicles, it is greater than 50%. Therefore, simple OM methodology is discarded for the calculation of the electric system emission factor.

On the other hand, the average OM method estimates the emission factor as the rate between the total CO_2 emissions and the net energy delivered by the system, considering both LCMR and HCMR power units. The simple-adjusted OM method also considers both types of resources. However, it considers the number of hours for which LCMR units are on the margin in each year. Its calculation procedure is more complex, but having the necessary data, it is considered the most appropriate method. Then, CM emission factor is computed from BM and simple-adjusted OM factors.

It can be observed from Tables 2 and 3 that these three emission factors (simple-adjusted OM, BM and CM) vary considerably according to the statistic indicator, i.e. mean, median or mode. In 2020 (Table 3) the difference achieves one order of magnitude.

Fig. 2 and 3 show the histograms of CM emission factor for solar or wind power generation projects (w_{OM} = 0.75 and w_{BM} = 0.25) in 2012 and 2020, respectively. The distribution of CM emission factor for projects other than wind or solar (w_{OM} = 0.50 and w_{BM} = 0.50) is presented in Fig. 4 (2012) and Fig. 5 (2020).

As mentioned in Background Section, the methodology used in this work has already been used by UTE and the private sector to estimate CO_2 emissions of the Uruguayan electric system. Some examples of the CM emission factors obtained by them are the following:

- 0.715 tCO_2/MWh, calculated for UTE’s wind farm project in “Sierra de los Caracoles”, in January 2010.
- 0.635 tCO_2/MWh, calculated by the company Fortuny Renovables Uruguay S.A. for the wind farm “Arbolito”, in 2008.
- 0.654 tCO_2/MWh, estimated by the company Energía Renovable Tacuarembó – Fenirol S.A. for a biomass power plant, in 2009.
- 0.6104 tCO_2/MWh, calculated by the company Generación Eólica Minas S.A. for the wind farm “Minas I”, in 2010.

The examples above calculate CM emission factors using simple-adjusted OM methodology. All projects are approved by the Climate Change Unit of the National Environmental Administration of Uruguay, and are certified or in the process of certification as CDM [6]. They are presented in this work in order to compare them with the CM emission factors obtained for 2012 using the tool incorporated to SimSEE. Even though the examples are for years previous to 2012, the power generation park has not changed significantly in those years, and it can be observed that the values used for the projects are between the ranges estimated by SimSEE. Specifically, they lie between the mean and mode (see columns 6 and 7 of Table 2, according to the type of project).

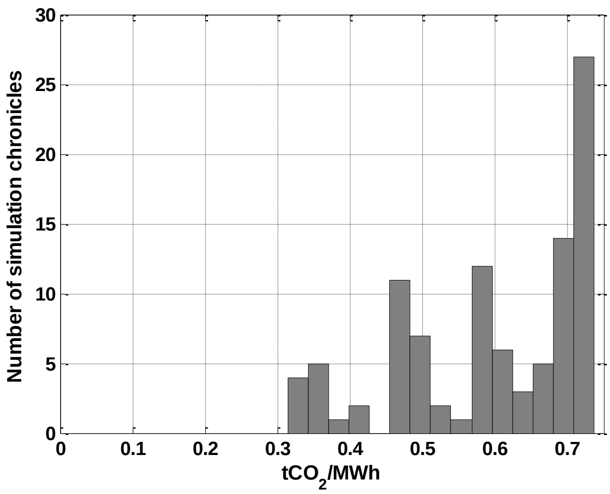

Fig. 2 Distribution of CM emission factor values in 2012 energetic scenario for solar or wind power generation projects (wOM=0.75 and wBM=0.25).

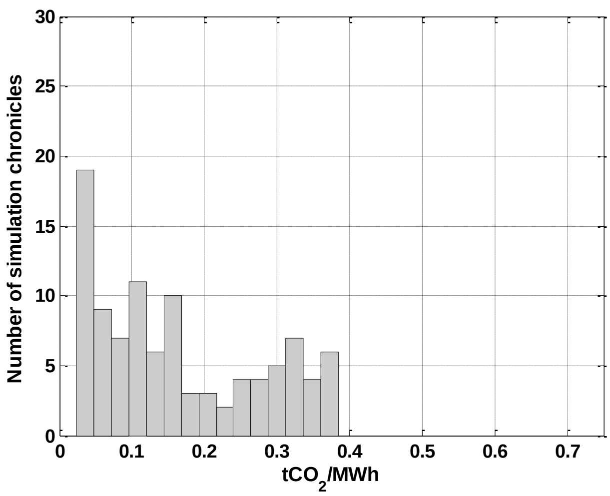

Fig. 3 Same as Fig. 2 but for 2020 energetic scenario.

As described in the section Scenarios of the Electric System, the most notorious changes in the generation pool between 2012 and 2020 are the great incorporation of renewable energies, especially wind power plants, and the replacement of oil-based fuels by others with lower emission factors, such as natural gas. With this hypothesis regarding the evolution of the national energy matrix, the emission factor drastically diminishes from 2012 to 2020, independently of the statistic indicator (mean, median, or mode).

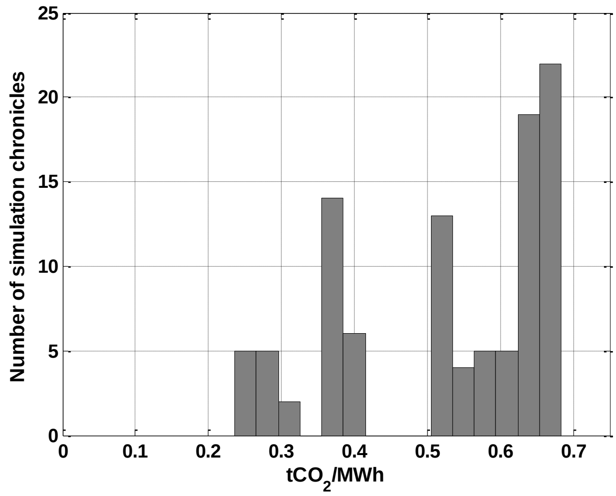

Fig. 4 Same as Fig. 2 but for projects other than solar or wind power generation (wOM=0.50 and wBM=0.50).

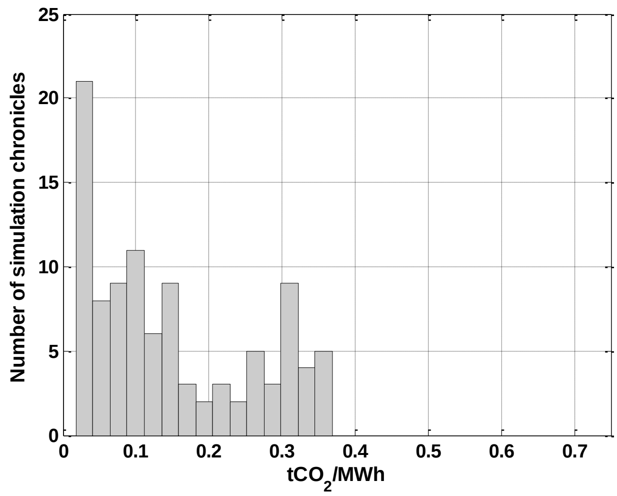

Fig. 5 Same as Fig. 2 but for 2020 energetic scenario and projects other than solar or wind power generation (wOM=0.50 and wBM=0.50).

Nevertheless, the distributions of the results present large variability, according to Fig. 2 to 5. In the 2012 energetic scenario the histograms present a clear negative asymmetry (Fig. 2 and 4). Consequently, the most frequent values are the highest ones, around 0.7 tCO_2/MWh. Conversely, in the 2020 scenario, the histograms show positive asymmetry (Fig. 3 and 5), meaning that the lowest emission factors are the most frequent ones, tending to 0 tCO_2/MWh.

It is important to highlight that, although the 2020 scenario is based on an optimal expansion plan of the Uruguayan electric system, it represents an unfavorable prospective scenario for the development of potential CDM projects.

6. Conclusions

On the one hand, we verified that the methodology incorporated to the SimSEE to estimate CO2 emission factor works as expected: for the year 2012, CM emission factors obtained using the tool are very similar to the values calculated by several projects certified or in the process of certification as CDM. This builds confidence in using the module to estimate the range of emissions in a given energetic scenario. Particularly, we believe it is a very useful tool to estimate emission factors in future scenarios. It is important to highlight that, due to uncertainties when performing the simulations, it is not possible to calculate a trustful unique value for the emission factor. Instead, its range of variation and distribution of values is obtained. These uncertainties are mainly associated with streamflow to hydroelectric dams, and availability of generators.

On the other hand, the evolution of the emission factor in the period 2012-2020 was analyzed using the new tool. The expected change of the Uruguayan energy matrix by 2020 involves a major incorporation of renewable energy sources with low carbon emissions and the replacement of oil-based fuels with natural gas. The CO_2 emission factor of the system drastically diminishes as the new power units are incorporated. Consequently, the potential production of CERs in certified CDM projects will likely decrease. Although a financial analysis is not performed in this work, if we consider the hypothesis that the prices of CERs will decrease due to the poor adhesion of countries to the second commitment period of the Kyoto Protocol (2013-2020), we estimate that CDM certification will not play an important role in fostering the development of projects based on non-traditional renewable energy sources in Uruguay.

Acronyms

BM: Build Margin Emission Factor.
CDM: Clean Development Mechanism.
CM: Combined Margin Emission Factor.
EF: Emission Factor in tCO_2/MWh.
GHG: Greenhouse Gases.
HCMR[1]: "High-Cost/May-Run". The HCMR resources are those that are not defined as LCMR (see LCMR definition below).
EB: Executive Board of the CDM.
LCMR: "Low-Cost/Must-Run". LCMR resources are those with a low marginal cost of generation, or those which are dispatched independently of the daily or seasonal network load.
OM: Operating Margin Emission Factor.
CERs: Certified Emission Reductions.
SimSEE: Electric Energy Systems Simulator.
UNFCCC: United Nations Framework Convention on Climate Change.
UTE: National Administration of Electric Power Plants and Electric Transmissions.

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