Supporting Information

Manuscript title: How You Count Carbon Matters: Implications of Differing Cookstove Carbon Credit Methodologies for Climate and Development Co-Benefits

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Pages: S1-S15

Figures:

Tables:

There are seven parts included in this section. This includes the emission factors for the different stoves included in the equations, equations for cookstove carbon credit calculation under both the Clean Development Mechanism (CDM) and Gold Standard (GS) methodologies, a table with global warming potential values applied in some calculations, a sensitivity analysis of the fraction of non-renewable biomass (*f*NRB) variable, a sensitivity analysis of regional global warming potential (GWP) values for black carbon (BC), some sample calculations using both CDM and GS methodologies and finally the references cited.

Emission Factors

Table S1 Emission factors (with uncertainty expressed as one standard deviation) used in this study's calculations for each different stove type in gC/kg unless otherwise noted. The values used in the CDM methodology were converted from a mass (gC/kg) to energy basis (tCO_2/TJ) in the calculations.

Stove	CO_2	CO	CH_4	NMHC	OC	BC	SO_2 (g/kg)	$PM_{2.5}$ (g/kg)	Production+
W-Tr-U[a]	382.28 ± 13.77	20.67 ± 1.67	2.92 ± 0.68	3.65 ± 0.44	2.15 ± 0.59	1.10 ± 0.25	0.27 ± 0.30	2.78 ± 0.60	N/A
W-Im-U[b]	391.75 ± 38.82	27.50 ± 5.25	3.00 ± 1.02	8.61 ± 2.39	1.41 ± 0.53	0.53 ± 0.19	0.27 ± 0.30	3.00 ± 0.72	N/A
W-Im-V[c]	425.45 ± 12.76	10.11 ± 1.82	0.45 ± 0.13	0.09 ± 0.08	0.72 ± 0.23	0.27 ± 0.08	0.27 ± 0.30	1.54 ± 0.20	N/A
W-Pat-V[d]	370 ± 21.35	22.33 ± 4.86	2.70 ± 0.93	4.10 ± 1.67	2.03 ± 0.66	0.93 ± 0.45	0.27 ± 0.30	3.23 ± 1.16	N/A
W-Gas-U[e]	463.64*	18.38*	1.74*	2.87*	0.59*	0.28*	0.27 ± 0.30	1.10*	N/A
W-Fan-U[e]	463.64*	1.67*	0.21*	0.97*	0.10*	0.06*	0.27 ± 0.30	0.20*	N/A
Coal-U[f]	684.55*	30.30*	7.73*	1.61*	2.35 ± 1.95	3.08 ± 2.32	0.15*	5.43 ± 3.03	0.52*
Coal-V[f]	736.36 ± 66.27	40.93 ± 15.55	2.64 ± 3.01	0.87 ± 0.90	2.35 ± 1.95	3.08 ± 2.32	0.88 ± 1.33	5.43 ± 3.03	0.52*
Char-U[g]	621.82 ± 9.27	111.43 ± 4.29	13.50 ± 4.50	2.13 ± 0.60	0.25 ± 0.32	0.18 ± 0.23	0.40*	0.40 ± 0.50	524.90 ± 6.41
Ker-U[h]	838.20 ± 28.39	5.65 ± 1.21	0.12 ± 0.07	5.05 ± 0.64	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.03	0.26 ± 0.15	179.84*
LPG-U[h]	842.06 ± 22.28	3.69 ± 0.85	0.22 ± 0.35	7.35 ± 2.04	0.07 ± 0.06	0.07 ± 0.06	N/A	0.52 ± 0.45	96.78*

+ The GS methodology includes production and transportation EFs of fuel in addition to direct fuel use where relevant. Production EFs were included in calculations for coal, charcoal, kerosene, and LPG fuels in the GS calculations (for CO_2, methane (CH_4) and nitrous oxide (N_2O) species in *Allowable Credits* scenarios only), but EFs for transportation of fuel were omitted, as these will vary widely based on the specific location and context of each project.

*No standard deviation values available in original studies.

[a] CO_2, CO, CH_4, NMHC[1,2]; OC, EC, $PM_{2.5}$[1]; SO_2[3] [b] CO_2, CO, CH_4, NMHC[2]; OC, EC, $PM_{2.5}$[4]; SO_2[3] [c] CO_2, CO, CH_4, NMHC[5]; OC, EC, $PM_{2.5}$[4]; SO_2[3] [d] CO_2, CO, CH_4, NMHC, OC, EC, $PM_{2.5}$[1]; SO_2[3] [e] CO_2, CO, CH_4, NMHC, OC, EC, $PM_{2.5}$[6]; SO_2[3] [f] CO_2, CO, CH_4, NMHC, SO_2, $PM_{2.5}$[5]; OC and EC fractions[7]; Production[8] [g] CO_2, CO, CH_4, NMHC, $PM_{2.5}$[9]; OC and EC fractions[7]; SO_2[3]; Production[10] [h] CO_2, CO, CH_4, NMHC, $PM_{2.5}$[2,5]; OC and EC fractions[7]; SO_2 (Value for Kero-U only[5]); Production[11]

CDM and GS Methodologies

CDM

The CDM methodology for calculating certified emission reduction (CER) credits[12] is as follows (emission reductions (**ER_y**) in tonne carbon dioxide equivalent (tCO_2e)/year/stove):

$$ER_y = B_{y,savings} * f_{NRB,y} * NCV * EF_{projected\ fossilfuel} \quad \textbf{(Equation S1)}$$

Where **$B_{y,savings}$** is the amount of fuel saved in tonnes through the project activities in year y, **$f_{NRB,y}$** is the fraction of non-renewable biomass in year y**, NCV** is the net calorific value of the woody biomass or other type of fuel, and **$EF_{projected\ fossilfuel}$** is the default emission factor, 81.6 tCO_2/TJ, representing the "substitution of non-renewable woody biomass by similar consumers" based on a mix of weighted fossil fuels. This represents the EF of the baseline stove in the project, usually a traditional stove. The equation still bases the amount of fuel saved on the actual baseline and project stoves' relative efficiencies and the amount of fuel needed for meeting energy requirements, but utilizes a misrepresentative default fossil-fuel EF. This is meant to provide conservative estimates without requiring the actual measurement of the traditional stove EFs, but does not reflect the actual emission reductions.

It is also important to note that the CDM does not allow fossil fuel based stoves (e.g., liquid petroleum gas (LPG)) to obtain credits unless switching from a high to low carbon intensive fossil fuel (e.g. coal to LPG). Therefore, in the results reported below there are two numbers included for the coal, charcoal, LPG and kerosene stoves: zero for the actual credits possible under the CDM and a second value for the credits that would be generated using *Equation S1* above, if switching from a traditional biomass based stove to fossil fuel stove was allowed.

GS

In the GS methodology to calculate GS voluntary emission reduction (VER) credits[13] estimates are more representative of actual emission reductions even when using allowed Intergovernmental Panel on Climate Change (IPCC) default EF values, than the CDM method as they calculate both baseline and project emissions. The equation is as follows:

$$ER_y = \sum_{b,p} N_{p,y} * U_{p,y} * (f_{NRB,b,y} * ER_{b,p,y,\,CO2} + ER_{b,p,y,\,non\text{-}CO2}) - \sum LE_{p,y} \quad \textbf{(Equation S2)}$$

Where $\sum_{b,p}$ is the sum of all the different baseline and project scenarios, $N_{p,y}$ is the number of 'technology-days' included in the project period in year y, here assumed to be 365 days, $U_{p,y}$ is the rate of usage of project technologies during year y as a fraction, here assumed to be 100%, $f_{NRB,b,y}$ is the fraction of non-renewable biomass for the baseline scenario in year y, $ER_{b,p,y,\,CO2}$ is the emission reductions of CO_2 when switching from the baseline to project technology in year y, measured in tCO_2 per day, $ER_{b,p,y,\,non\text{-}CO2}$ is the amount of emission reductions of non-CO_2 emissions, methane (CH_4) and nitrous oxide (N_2O), when switching from the baseline to project technology in year y, in units of tCO_2e per year, for which only CH_4 is included in this study's equations, and $LE_{p,y}$ is leakage for the project scenario in year y, here assumed to be zero for all calculations.

Global Warming Potentials (GWP)

Table S2 GWP_{100} values for all species included in the study.

Species	**GWP_{100}**
Kyoto Gases	
CO_2	1[14]
CH_4	25[14]
Other Species	
CO	1.9[14]
NMHC	3.4[14]
BC*	455[15]
OC	-35[15]
SO_2	-76[16]

*New estimates suggest using a value of 900 (estimated within an uncertainty of 120 to 1800)[17]. Here the more conservative estimate of 455 is used. If a GWP_{100} value of 900 was employed estimates of carbon credits in the *All Species* scenarios would be greatly increased for all positive carbon credit generating scenarios. See *Regional GWP Sensitivity Analysis* here in the Supporting Information for a sensitivity analysis of regional GWP values for BC.

fNRB Sensitivity Analysis

The methods to calculate the *f*NRB lack specificity in both methodologies though GS provides marginally more detailed guidelines than CDM. Under both approaches high levels of uncertainty through coarse estimates and inconsistent methodological approaches are incorporated into estimates of the *f*NRB. To demonstrate the variability that different values of *f*NRB can create, a sensitivity analysis is conducted. Carbon credits were calculated under both methodologies using *Equation S1* and *Equation S2,* for all stoves applying values for the *f*NRB of: 25%, 50%, 75%, 85% and 95%. The majority of reported values in actual projects are in the range of 75-100%. Including the values 25% and 50% demonstrate the potential variability in carbon credits calculated if the reported range was extended.

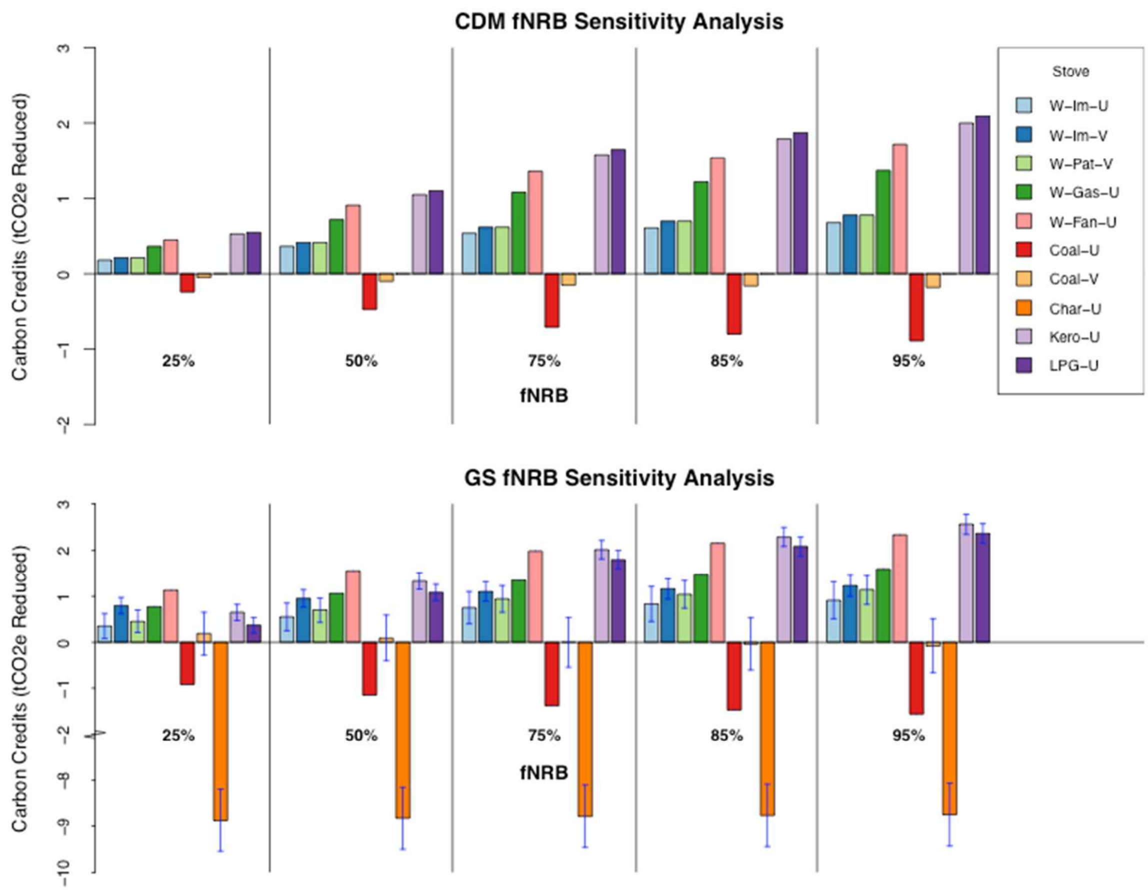


Figure S1 Sensitivity analyses for the *f*NRB under both the CDM and GS using values of 25%, 50%, 75%, 85% and 95%. Note the difference in scale as the GS values span a much larger range of values than the CDM. Since CDM calculations employ a default EF there is no uncertainty represented for any of these values. For the GS calculations, values of standard deviation were not available for the EFs of the W-Gas-U, W-Fan-U and Coal-U stoves and therefore uncertainty is not represented for these stoves either.

Figure S1 compares the different stove scenarios under CDM and GS when using different values of the *f*NRB in the calculations. In general the higher the value of the *f*NRB the higher the amount of carbon credits per year per stove calculated under both methodologies with the exception of Coal-U, Coal-V and Char-U, in which the inverse relationship is true (exception: Char-U under CDM, where it equaled zero when using all different values of the *f*NRB). For the other seven stoves the difference of carbon credits calculated when using 25% and 95% values of *f*NRB ranged from 0.44 to 1.99 carbon credits with an average difference of 0.68 carbon credits under the GS and 0.62 carbon credits under the CDM. For the *f*NRB values of 75% and 95% the difference in the number of credits calculated for the seven stoves ranged from 0.13 to 0.57 with an average difference of 0.18 for CDM and 0.20 for GS. For the fossil fuel stoves the differing values of the *f*NRB have an especially large impact on the number of carbon credits calculated with high values of the *f*NRB greatly increasing the number of carbon credits calculated.

The large difference between calculations utilizing *f*NRB values of 25% and 95% demonstrates the substantial variability included in calculations. This can significantly change the amount of carbon credits calculated especially when applying the differences per individual stove to an entire project for example with 10,000 or 21,500 stoves. In the range of values most commonly reported in actual projects, 75%-95%, the variability is reduced. Still the scenario with the largest difference, GS LPG-U, had over a 0.5 tCO_2e difference in credits per stove between this range. At the much larger project scale, even small differences in carbon credits calculated based upon differences in the value of the *f*NRB applied, can have huge impacts potentially greatly changing the amount of income earned. In general, the biomass stoves seem to perform relatively better than the fossil fuel stoves at lower values of *f*NRB. Therefore even though the fossil fuel stoves obtain high values of carbon credits when employing high values of the *f*NRB, if the *f*NRB was low, such projects may not make financial sense in the context of carbon credits.

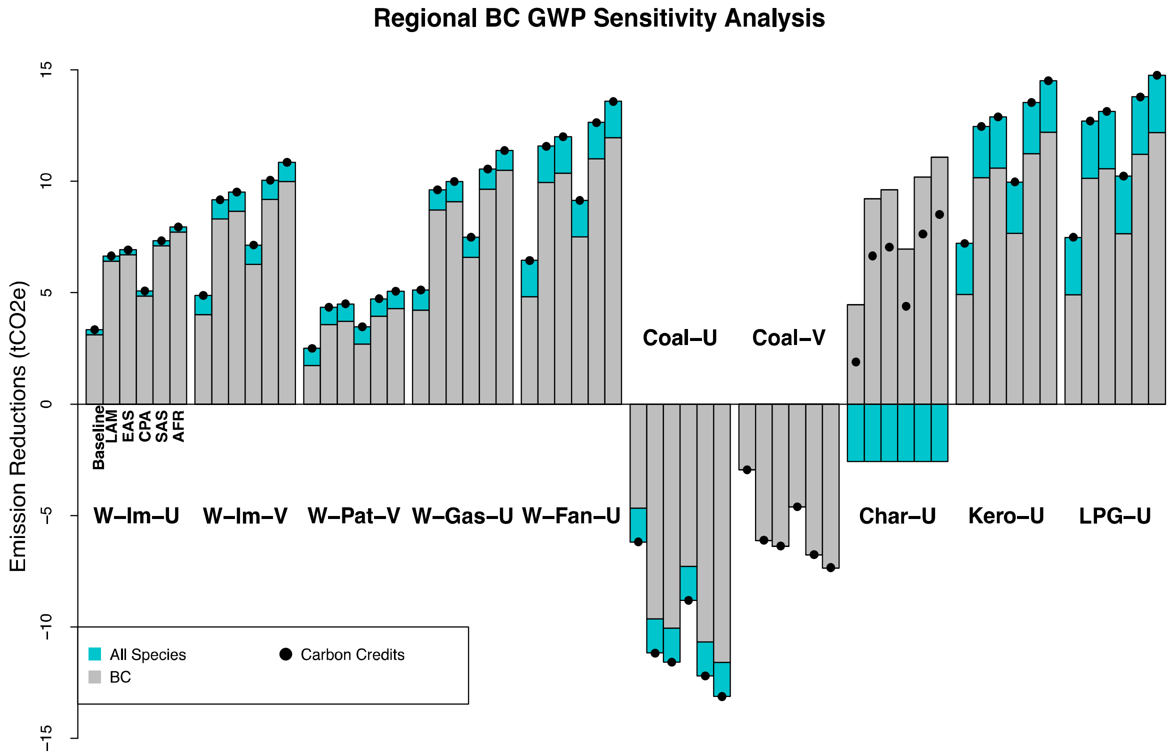
The current high levels of *f*NRB in actual projects may reflect the fact that: a) cookstove projects at lower levels of *f*NRB are simply not financially viable, b) the flexibility in methods and uncertainties in data allow project developers wide latitude in determining the *f*NRB and therefore maximize their carbon credits, or c) a combination of both these potential influencing factors. If uncertainty in the calculations of the *f*NRB was reduced and actual values of the *f*NRB were deemed to be lower than the current high values, this could significantly change the amount of credits calculated in all scenarios. As the uncertainty and lack of specific guidance for calculating this number may be resulting in inaccurately reported emission reductions[18], this is an area where more research is needed to reduce the uncertainty incorporated in these values.

Regional GWP Sensitivity Analysis

Black carbon (BC) has been identified to have the second greatest global warming impact after CO_2[17]. BC is a particulate created through incomplete combustion. Residential burning of solid fuels is one of the top four highest BC emitting activities[17]. A particulate which strongly absorbs sunlight, its climate forcing impacts are complex and continue to be the subject of ongoing research. It's climate forcing comes from its impact on: incoming solar radiation (through absorption and scattering; cloud properties; and snow and ice after deposition by changing albedo. As it is a short-lived particle existing in the atmosphere from a period of days to weeks, its impacts are mostly regional[19,20]. In the analyses in this study, one GWP value was applied (see *Table S2*), but to demonstrate the potential regional variability here a sensitivity analysis of regional GWP values is included. Using

Rypdal et al. (2009)[21] 100 year GWP estimates for regions made up mostly of developing countries, areas where there is the highest use of cookstoves, are compared using the *GS All Species* scenarios. Since the analysis here is focusing on the differences in potential emission reductions of BC, all the other species are visually grouped together in *Figure S2*. The regions included from Rypdal et al. (2009)[21] include Latin America (LAM; GWP 950), East Asia (EAS; GWP 990), Centrally Planned Asia (CPA; where China is the dominant country; GWP 750), South Asia (SAS; where India is the dominant country; GWP 1110) and Africa (AFR; GWP 1140).

As all of the regional GWP values are larger than that applied in the rest of the study's scenarios (*Table S2*), all of the potential regional carbon credit values in the sensitivity analysis are greater than the baseline (from ~1 to 7.3 credits more; in all scenarios generating a positive amount of credits, i.e., in all but Coal-U and Coal-V). As AFR has the highest regional GWP it also produces the highest amount of credits with CPA producing the least. Therefore if these regional considerations were taken into account and BC was accounted for under a carbon credit methodology, strategically it would make the most sense to register projects in the AFR or SAS regions. For example, depending on the scenario the AFR region calculated between 1.6 (W-Pat-V) to 4.5 (Kero-U and LPG-U) credits more than CPA.



Here sample calculations for calculating carbon credits for both the *Allowable Credits* and *All Species* scenarios under CDM and GS are demonstrated. Switches from the W-Trad-U stove to two other stoves are included: a biomass stove, W-Im-U and the Char-U stove which has production emissions associated with the fuel in the GS calculations.

GWP values in *Table S2* are used for the different species included in the calculations and the value for the *f*NRB is assumed to be 75% in these scenarios. The EFs used in each demonstrated scenario are outlined in *Table S3* (for CDM) and *Table S4* (for GS).

CDM Calculations

Table S3 CDM emission factors in tCO_2/TJ for all the different species used in both the *Allowable Credits* and *All Species* scenarios. Values for other variables in the CDM equation are also included.

Stove	B_y (t/yr)	NCV (TJ/t)	Thermal Efficiency	$EF_{projected\ fossilfuel}$	EF_{CO2}	EF_{CH4}	EF_{CO}	EF_{NMHC}	EF_{OC}	EF_{BC}	EF_{SO2}
W-Trad-U	2.69	0.015 (wood)	18%	81.6	93.45	0.71	5.05	0.89	0.53	0.27	0.01
W-Im-U	2.07	0.015 (wood)	23%	81.6	95.76	0.73	6.72	2.10	0.34	0.13	0.01
Char-U	1.58	0.026	18%	81.6	87.53	1.90	15.69	0.30	0.04	0.03	0.01

CDM Equation: *Allowable Credits*

$ER_y = B_{y,savings} * f_{NRB,y} * NCV * EF_{projected\ fossilfuel}$

(See *Equation S1* for description of variables)

Where

$B_{y,savings} = B_{old} * (1-(N_{old}/N_{new})$

$B_{old} = B_y$ for the baseline stove in this case W-Trad-U

N_{old} = the thermal efficiency for the baseline stove

N_{new} = the thermal efficiency for the project stove

Calculations

CDM Allowable Credits	
W-Trad-U W-Im-U	W-Trad-U Char-U
<u>ER_y</u> 0.54 = 0.58*0.75*0.015*81.6 <u>$B_{y,savings}$</u> 0.58 = 2.69*(1-(0.18/0.23))	<u>ER_y</u> 0 = 0*0.75*0.015*81.6 <u>$B_{y,savings}$</u> 0 = 2.69*(1-(0.18/0.18))

CDM Equation: *All Species*

$ER_y = ER_{y,CO2} + \sum ER_{y,CH4,\ CO,\ NMHC,\ OC,BC,SO2}$

An example of calculation for one of the *All Species*, species:

$ER_{y,CH4} = B_{y,savings}*NCV*EF_{CH4}*GWP_{100,CH4}$

The ER then gets calculated for all other species and a sum of their total ER is added to the $ER_{y,CO2}$. Below only one example for the other species is included, CH_4, but the same equations are applied to the others and the ER_y values displayed below are a sum when all species are included.

Calculations

CDM All Species	
W-Trad-U W-Im-U	W-Trad-U Char-U
ER_y = 1.79 $ER_{y,CO2}$ 0.54 = 0.58*0.75*0.015*93.45 $ER_{y,CH4}$ 0.16 = 0.58*0.015*0.71*25 $B_{y,savings}$ 0.58 = 2.69*(1-(0.18/0.23))	ER_y =0 $ER_{y,CO2}$ 0 = 0*0.75*0.015*87.53 $ER_{y,CH4}$ 0 = 0*0.015*1.90*25 $B_{y,savings}$ 0 = 2.69*(1-(0.18/0.18))

Gold Standard Calculations

Table S4 GS emission factors in tCO_2/tFuel for all the different species used in both the *Allowable Credits* and *All Species* scenarios. Values for other variables in the GS equation are also included.

Stove	**B_y (t/yr)**	**EF_{CO2}**	**EF_{CH4}**	**EF_{CO}**	**EF_{NMHC}**	**EF_{OC}**	**EF_{BC}**	**EF_{SO2}**	**Production (Includes EF_{CO2} and EF_{CH4})**
W-Trad-U	2.69	1.40	0.01	0.08	0.01	0.0079	0.0040	0.0002	N/A
W-Im-U	2.07	1.44	0.01	0.10	0.03	0.0052	0.0019	0.0002	N/A
Char-U	1.58	2.28	0.05	0.41	0.01	0.0009	0.0007	0.0003	1.92

GS Equation: *Allowable Credits*

$ER_y = \sum_{b,p} N_{p,y} * U_{p,y} * (f_{NRB,b,y}*ER_{b,p,y,\,CO2}+ER_{b,p,y,\,non\text{-}CO2}) - \sum LE_{p,y}$

(See *Equation S2* for description of variables)

Assumptions:

$N_{p,y} = 365$

$U_{p,y}$ = 100%

$f_{NRB,b,y}$ = 75%

$LE_{p,y}$ = 0

Where

$ER_{b,p,y}$ is the sum of $ER_{b,p,y,\ CO2}$ and $ER_{b,p,y,\ CH4}$:

$ER_{b,p,y,\ CO2} = ((B_{p,y}*EF_{p,CO2})/365)-((B_{b,y}*EF_{b,CO2})/365)$

($B_{p,y} = B_y$ for the project stove and $B_{b,y} = B_y$ for the baseline stove, same for EF_p and EF_b, but for EFs)

$ER_{b,p,y,\ CH4} = ((B_{p,y}*EF_{p,CH4}*GWP_{100,CH4})/365)-((B_{b,y}*EF_{b,CH4}* GWP_{100,CH4})/365)$

To Include Emissions from Fuel Production in Calculation
(for Coal, Charcoal, LPG and Kerosene fuels only)

$ER_{y,final} = ER_y - ER_{prod}$

Where

$ER_{prod} = (EF_{prod,CO2}*B_{p,y})+(EF_{prod,CH4}*B_{p,y}* GWP_{100,CH4})$

Calculations

GS Allowable Credits	
W-Trad-U W-Im-U	W-Trad-U Char-U
<u>ER_y</u> 0.75 = 365*1*(0.75*0.0022+0.0004)-0 <u>$ER_{b,p,y,\ CO2}$</u> 0.0022 = ((2.69*1.40)/365)-((2.07*1.44)/365) <u>$ER_{b,p,y,\ CH4}$</u> 0.0004 = ((2.69*0.01*25)/365)-((2.07*0.01*25)/365)	<u>ER_y</u> -8.78 = ((365*1*(0.75*0.0005+-0.0034)-0))+-7.68 <u>ER_y</u> -1.10 = (365*1*(0.75*0.0005+-0.0034)-0) <u>$ER_{b,p,y,\ CO2}$</u> 0.0005= ((2.69*1.40)/365)-((1.58*2.28)/365) <u>$ER_{b,p,y,\ CH4}$</u> -0.0034= ((2.69*0.01*25)/365)-((1.58*0.05*25)/365) <u>ER_{prod}</u> 7.68 =(1.58*1.80)+(1.58*0.12*25)

GS Equation: *All Species*

The calculations for the *All Species* scenarios under GS follow the same equation as in the *Allowable Credits* scenario, but instead of just including CH_4, ER for each additional species is calculated then summed. For these calculations production EF were not included because production EF for all additional species were not available from the literature used.

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