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Article

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Avoided emissions of a fuel-efficient biomass cookstove dwarf embodied emissions

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ABSTRACT

Three billion people cook their food on biomass-fueled fires. This practice contributes to the anthropogenic radiative forcing. Fuel-efficient biomass cookstoves have the potential to reduce CO_2-equivalent emissions from cooking, however, cookstoves made from modern materials and distributed through energy-intensive supply chains have higher embodied CO_2-equivalent than traditional cookstoves. No studies exist examining whether lifetime emissions savings from fuel-efficient biomass cookstoves offset embodied emissions, and if so, by what margin. This paper is a complete life cycle inventory of "The Berkeley–Darfur Stove," disseminated in Sudan by the non-profit Potential Energy. We estimate the embodied CO_2-equivalent in the cookstove associated with materials, manufacturing, transportation, and end-of-life is 17 kg of CO_2-equivalent. Assuming a mix of 55% non-renewable biomass and 45% renewable biomass, five years of service, and a conservative 35% reduction in fuel use relative to a three-stone fire, the cookstove will offset 7.5 tonnes of CO_2-equivalent. A one-to-one replacement of a three-stone fire with the cookstove will save roughly 440 times more CO_2-equivalent than it "costs" to create and distribute. Over its five-year life, we estimate the total use-phase emissions of the cookstove to be 13.5 tonnes CO_2-equivalent, and the use-phase accounts for 99.9% of cookstove life cycle emissions. The dominance of use-phase emissions illuminate two important insights: (1) without a rigorous program to monitor use-phase emissions, an accurate estimate of life cycle emissions from biomass cookstoves is not possible, and (2) improving a cookstove's avoided emissions relies almost exclusively on reducing use-phase emissions even if use-phase reductions come at the cost of substantially increased non-use-phase emissions.

1. Background and motivation

Three billion people rely on biomass combustion to cook their food which contributes to the increasing stock of anthropogenic greenhouse gases and aerosols (The World Bank, 2011; Bond et al., 2004). Renewable biomass (RB) and non-renewable biomass (NRB) distinguish harvested products that leave net standing biomass stocks unchanged or depleted, respectively. Either RB or NRB can be utilized in cooking. While biomass-burning stoves generate over 1 billion tonnes of CO_2 annually (The World Bank, 2011), some of these CO_2 emissions come from combustion of RB and therefore do not increase the anthropogenic stock of CO_2. However, in many parts of the developing world biomass resources are not sustainably harvested. This is true in the regions around internally displaced peoples' camps in North Darfur, Sudan where 55% of fuel wood is NRB (Codipietri and Drigo, 2010). Incomplete combustion of RB or NRB will generate non-CO_2 climate-forcing products of incomplete combustion (PIC) such as methane, non-methane hydrocarbons, and black carbon aerosols. These PICs have significant radiative forcing properties, and black carbon is estimated to be the second or third largest anthropogenic contributor to radiative forcing after CO_2 and methane (Bailis et al., 2003; Ramanathan and Carmichael, 2008). In the case of NRB combustion, displacement of traditional cookstoves such as three-stone fires (TSF) (Fig. 1) and inefficient earthen stoves with fuel-efficient cookstoves has the potential to reduce net CO_2 emissions by as much as 25–50% (The World Bank, 2011; Barnes et al., 1994). In this paper, the combined 100-year global warming potentials (GWP) of anthropogenic CO_2 and PICs are referred to in terms of CO_2-equivalent (CO_2-e) emissions.

Unlike a TSF or basic mud stove, a fuel-efficient cookstove has embodied CO_2-e stemming from the use of modern materials in

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Fig. 1. Inefficient three-stone biomass fire in Darfur, Sudan.

construction and the energy required to manufacture and transport the cookstove to the user. Many cookstoves including the popular EcoZoom (formerly StoveTec), Envirofit, and BDS are manufactured outside the customers' home country using modern energy-intensive materials and subsequently transported thousands of kilometers through complex supply chains to their points of use. To date, the dominant discussion in the literature has been the use-phase emissions of fuel-efficient cookstoves (MacCarty et al., 2008, 2010; Jetter and Kariher, 2009; Panwar et al., 2009; Roden et al., 2009; Barnes et al., 1994). These analyses do not consider the impact of cookstove materials, manufacturing, transportation, and end of life. Informally, many cookstove proponents assume that cookstoves will pay off embodied emissions, however, to our knowledge, this assumption has not been substantiated in the literature. Afrane and Ntiamoah (2012) compared the environmental impact of various cooking fuels used in Ghana and investigated the differences between charcoal, wood, propane, biogas, kerosene, and electricity. While fuel processing emissions were taken into account, the infrastructure required for each fuel type was neglected if the data was not readily available. Bailis et al. (2003) investigated the emissions of six types of wood and charcoal-burning cookstoves and compared their 20-year GWP with the TSF. In that study the non-use-phase emissions such as embodied CO_2-e in materials, manufacturing, and transportation necessary to distribute stoves were not considered when the cookstove's GWP were calculated. While the literature does provide some preliminary work on non-use-phase impact of cookstoves (Jungbluth, 1997), it does not provide careful analysis or case studies of embodied CO_2-e in cookstoves compared to the CO_2-e savings from their use.

This paper is one of the first analyses of the life cycle CO_2-e impact of a fuel-efficient biomass cookstove that is being produced, disseminated, and used at a scale of tens of thousands of units. We have selected to study the Berkeley–Darfur Stove (BDS) disseminated in Darfur by the non-profit Potential Energy (PE), formerly named The Darfur Stoves Project. We analyze this stove as an exemplar to obtain insights into various life phase emissions of similar advanced cookstoves.

The situation in Sudan is comparable to that in much of the developing world both in terms of choice and quantity of fuel used for daily cooking. 56% of the Sudanese population uses wood as cooking fuel (Legros et al., 2009) with a daily consumption of 5–8 kg per household, both in line with developing world averages, especially in Africa (Fig. 3) (Hutton et al., 2006). Fig. 2 demonstrates that the BDS is a good choice for this analysis because its thermal efficiency and CO_2-e emission reduction capability are comparable to those of other peer naturally drafted wood-burning cookstoves (Jetter et al., 2012). As of June 2015, PE has disseminated about 47,000 BDS units in Darfur; the scale of BDS dissemination allows us to estimate the impact of a cookstove program operating at large scale. Given the aforementioned factors, our life cycle analysis of the BDS is likely to be generalizable to other cookstoves with similar design, dissemination scales, materials, fuels, lifetimes, and frequencies of use. Because the BDS's design and intended impact are similar to other cookstove programs, we intend the conclusions of this study to be applicable to other cookstove programs worldwide such as Envirofit, GIZ, Cookstoves for Africa, Project Gaia, UGASTOVE, and EcoZoom.

2. The life of the Berkeley–Darfur Stove

The BDS is manufactured at Shri Hari Industries (SHI) in Mumbai, India. In order to reduce manufacturing cost and improve quality, BDS parts are manufactured from sheet metal in India, shipped as unfolded flat kits to Sudan, and assembled by internally displaced persons at a workshop in Al-Fashir, Darfur. Because Sudan lacks access to materials and sophisticated manufacturing facilities, the BDS is significantly less expensive and of higher quality when manufactured in India. After manufacturing operations, BDS flat kits are trucked to the port in Mumbai and shipped 4400 km to Sudan. In Sudan, Sustainable Action Group (SAG), one of PE's on-the-ground partners, loads the flat kits onto a truck and transports them 1800 km from Port Sudan to Al-Fashir, Darfur (Fig. 5).

In Al-Fashir, PE and SAG have setup a 50 m^2 assembly shop that employs 12 people and can build 160 stoves per day (Fig. 7). Sheet metal components are folded into their final geometry using mostly human-powered tools. An air compressor is used to operate riveting equipment, but its contribution to manufacturing-phase emissions is assumed to be negligible. Finally each stove undergoes a quality control check and serialization before it is trucked to customers in camps, peri-urban towns, and villages.

The BDS has an expected lifetime of five years. Surveys have shown that these stoves displace traditional cooking fires and are being used up to three times per day for the five-year service life of the stove (Darfur Stoves Project, 2011). It is believed that the end of a BDS's life comes when its steel components have corroded to such a degree that the stove is no longer functional.

3. Impact

3.1. Materials

Table 1 shows the bill of materials, sans fasteners, that comprises each flat kit (shown pictorially in Fig 6). Based on purchase order records from over 30 thousand flat kits, SHI reported that these masses are within $\pm 10\%$ accuracy. Jindal Steel or various suppliers from Russia provide the IS 513 mild steel sheet for the body. The mild steel rods come from two sources: one from Delhi, the other from China. Cast iron grates are produced in Gujarat, and the 430-series stainless steel for the firebox wall is a Mumbai-sourced product. Finally, neem wood is used for the handles; emissions from neem are assumed negligible.

Upon request, World Steel Association generously provided CO_2-equivalent industry average life cycle inventory data for finished cold-rolled coil (FCRC) with CO_2-e emissions based on CML2001 100 year GWP (Crawford, 2012).

CO_2-equivalent emissions per kg of cold-rolled coil were used to estimate the life cycle global warming potential for mild sheet as well as providing a conservative estimate for the mild steel rods and cast iron; separate CO_2-e data for cold-rolled 300-series stainless were used to estimate the impact of the firebox. The CO_2-equivalence of fasteners was assumed to be negligible.

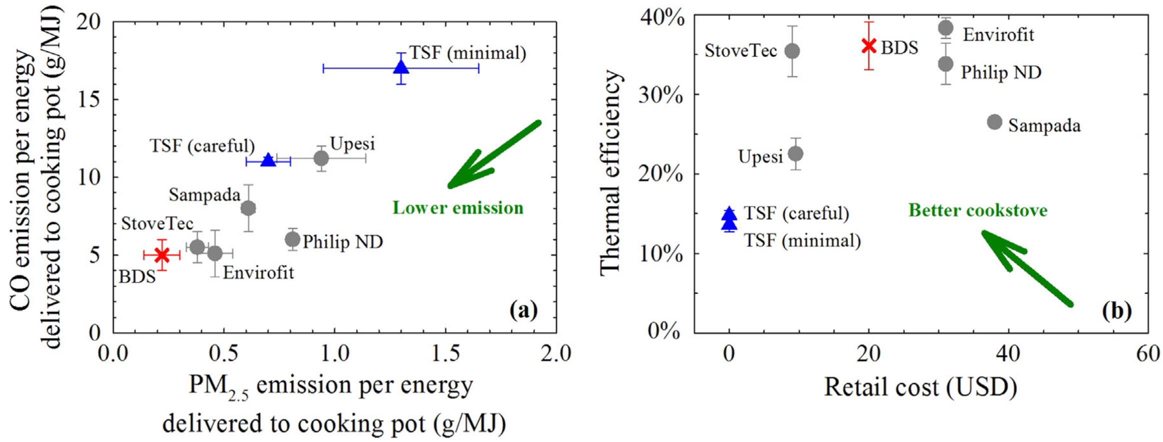

Fig. 2. CO vs. PM2.5 emissions data for high power low-moisture wood and thermal efficiency vs. retail cost and data from Jetter et al. (2012). Retail cost data collected from various sources in 2011 by Dr. Yungang Wang of LBNL.

Fig. 3. Women cooking over a three-stone fire in Darfur, Sudan.

Table 1
Average mass and average waste of each material that comprises a stove.

Material	Part mass (kg) + waste% (kg)	Total mass (kg)
Mild steel sheet	3.18 + 10 (0.32)	3.50 ± 0.35
Mild steel rod	1.12 + 2.5 (0.03)	1.14 ± 0.11
Stainless steel sheet	0.39 + 25 (0.10)	0.49 ± 0.05
Cast iron	1.80 + 7.5 (0.14)	1.94 ± 0.19
Neem wood	0.06 + 18 (0.01)	0.06 ± 0.01

Although we understand that steel is heavily recycled and almost never supplied 100% virgin, we make the worst case assumption that the steel is 100% virgin. For virgin steel, World Steel estimates 1.9 kg of CO_2-equivalent per kg steel on a 100 year GWP basis; this agrees well with independent estimates made by Tata Steel (World Steel Association, 2011; Tata Steel, 2012). The International Stainless Steel Forum (2010) estimates the cradle to gate CO_2-e of cold-rolled 300-series stainless coil at 4.0 kg per kg of coil. Using the conservative estimates, 7.1 ± 0.7 kg of material used to make a single BDS flat kit corresponds to 14.6 ± 1.4 kg of CO_2-equivalent released on a 100-year GWP basis.

3.2. Manufacturing

In a four-month period in 2011, SHI manufactured 6200 BDS flat kits and consumed a total of 2872 kWh of electricity. SHI undertook other manufacturing activities during this time, and they estimate that 50 ± 15% of their total electricity bill (1436 ± 431 kWh) was used towards production of BDS kits. Ghosh (2010) reported that 79% of India's grid electricity comes from thermal power plants whose CO_2-e intensity is 0.98 tons of CO_2 per MWh. Assuming the worst-case scenario where the entirety of SHI's power comes from thermal power plants such as those reported by Ghosh, the electricity used by SHI to make 6200 flat kits is equivalent to 0.2 ± 0.1 kg of CO_2 per stove. Stove assembly in Darfur is assumed to have negligible impact.

3.3. Transportation

Transportation of the BDS comprises six steps as shown in Table 2. Calculations are based on a 10-ton diesel truck with a 6750 kg weight limit, 40 m^3 volume limit, and 4.25 km/l diesel efficiency at 2.8 kg_{CO_2}/l diesel CO_2 intensity. Shipping emissions are taken from the literature provided by shipping agencies and use worldwide fleet averages (CEFIC and ECTA, 2011). Transportation emissions are reported as a range from the minimum mileage associated with the transportation activity to a conservative 150% of the minimum mileage to account for possible detours. Total emissions associated with transporting the BDS are estimated to be between 1.7 and 2.6 kg_{CO_2}/stove.

Table 2
Life cycle emissions associated with transportation.

Trip	Minimum travel (km)	Unit moved per stove	kg CO_2 per unit moved	Minimum to 150% Minimum CO_2 impact (kg)	
Materials trucked to SHI	25	5.13 kg	9.8E−05	1.3E−02	1.9E−02
Grate trucked to SHI	820	1.80 kg	9.8E−05	1.4E−01	2.2E−01
Kits trucked (SHI to Mumbai port)	140	6.49 kg	9.8E−05	8.9E−02	1.3E−01
Kits shipped (Mumbai to Port Sudan)	4400	6.49 kg	1.0E−05	2.9E−01	4.3E−01
Kits trucked (Port Sudan to Al-Fashir)	1800	6.49 kg	9.8E−05	1.1	1.7
Stoves trucked (Al-Fashir to customers)	235	0.02 m^3	1.6E−02	7.3E−02	1.1E−01
Total				1.7	2.6

Fig. 4. Berkeley–Darfur Stove in use in an IDP camp.

3.4. *Use*

Accurately estimating CO_2 emissions from the use-phase of a cookstove, as deployed in the field, is difficult. Laboratory testing protocols are often defined in the interest of a uniform test procedure, while in the real world a stove usage behavior varies widely. Additionally, laboratory testing is conducted indoors under quiescent conditions; as can be seen in Fig. 4, cooks in Darfur have poor shelter from the outdoor breeze or may cook outside exposed to the wind. This wind can have a substantial negative impact on TSF thermal efficiency and further spread the difference in performance between the BDS and TSF. We refer the reader to several detailed discussions on the influence of testing methods on cookstove performance (Willson et al., 2011; Smith et al., 2007; Johnson et al., 2010).

Researchers from Lawrence Berkeley National Laboratory (LBNL) and PE completed field tests of cookstoves similar in design to the BDS in 2008 (Galitsky et al., 2006), laboratory water boiling tests (WBT) of the BDS and TSF in 2010 (Preble et al., 2014), and a 140-household survey of BDS users 6–8 months after dissemination in 2010 (Darfur Stoves Project, 2011). Each of these tests revealed that the BDS significantly out-performed traditional TSFs, however results were not always in agreement. Testing of stoves in 2008 suggested a 50% reduction in mass of fuelwood per cooking cycle, however, the sample size was very small ($n=4$) (Galitsky et al., 2006). The 2010 field survey showed a 55% reduction in expenditures on fuel wood with 95% CI [51%, 59%] while the fuelwood price remained unchanged over this period (Darfur Stoves Project, 2011). Finally, the 2010 laboratory WBTs showed a reduction in fuel use of 35% with 95% CI [30%, 39%]. For this study, we use the most conservative data from 2010 laboratory WBTs while recognizing that WBTs are often a weak proxy for in-field performance (Table 3).

In this paper "moist wood" refers to wood containing any moisture (as it will in the field) and "dry wood" refers to the mass of wood if all moisture were to be removed. Daily moist wood use was estimated using survey data about meals eaten per day, moist wood use per meal, and laboratory-determined ratio of BDS to TSF moist wood consumption to complete a WBT. We normalize TSF emissions to the assumed five-year BDS lifetime. Baseline moist wood use is calculated using 2005 survey data from 50 Darfuri families using TSFs. These families ($n=50$) reported using 2.0 ($\sigma=1.0$) kg of moist wood per meal and cooked 3.0 ($\sigma=1.0$) meals per day. Using laboratory testing data of the BDS we estimate 9% average water content in moist wood (Preble et al., 2014). In the WBT, it was observed that the BDS ($n=21$) used 368 ($\sigma=34$) g of dry wood to complete the WBT; the TSF ($n=20$) required 564 ($\sigma=75$) g. From lab data, we calculate the average percent fuel used by the BDS vs. the TSF to be 65% and assume that this ratio can be applied to BDS vs. TSF dry wood consumption in the field.

Fig. 8 illustrates the breakdown of CO_2-e emission factors for a three-stone fire and the Berkeley–Darfur Stove. Consistent with prior studies, PICs represent a significant portion of the total radiative forcing of emissions (MacCarty et al., 2008; Kirchstetter et al., 2010; Ramanathan and Carmichael, 2008). To calculate CO_2-e, CO_2 and black carbon emission factors were taken from Preble et al. (2014) laboratory data while organic matter (OM) and non-CO_2 gas contributions were taken from MacCarty et al. (2008) using MacCarty's "rocket-style stove" as a proxy for the BDS. 100-year GWP for black carbon was assumed to be 680 (Bond and Sun, 2005) while OM was assumed to be −50 as in prior work by MacCarty et al. (2008). It is interesting to note in Fig. 8 that the total emissions factor of CO_2-e attributable to PICs is almost identical for the TSF and BDS (1150 vs. 1110 gCO_2-e/kg dry wood for the TSF and BDS, respectively); the BDS has a higher contribution from aerosols, namely black carbon, but this is balanced

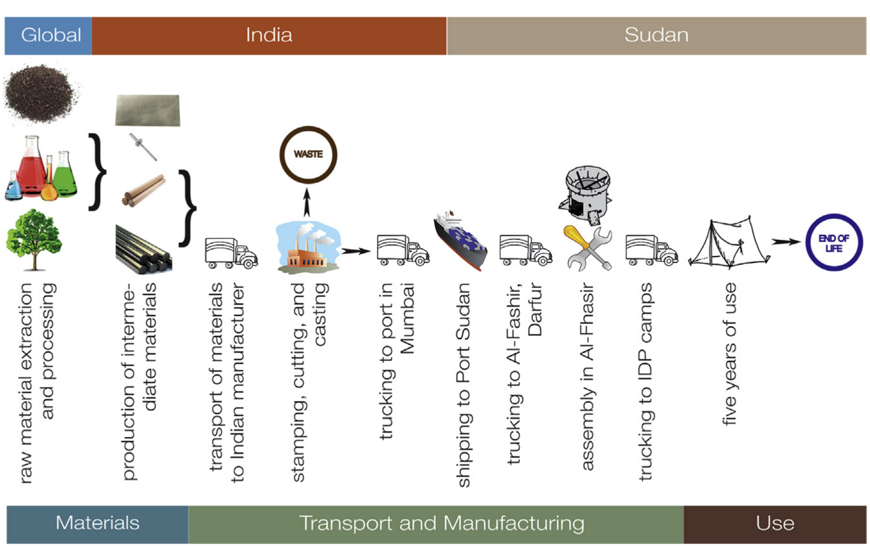

Fig. 5. Life of the Berkeley–Darfur Stove.

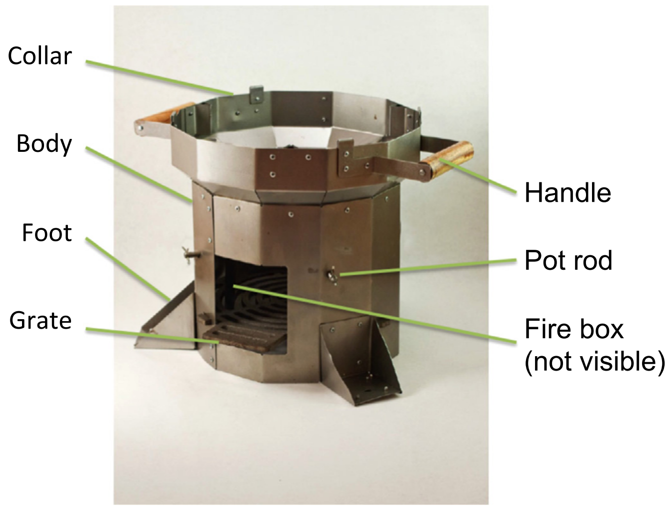

Fig. 6. Parts of the Berkeley–Darfur Stove.

Fig. 7. Berkeley–Darfur Stove assembly shop in Al Fashir, Sudan.

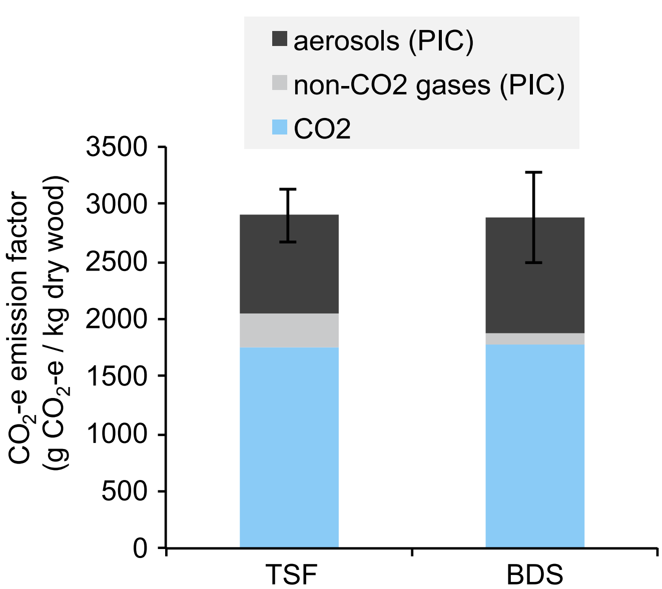

Fig. 8. CO_2-e emission factors (100 year basis) are shown for a TSF and the BDS. "Aerosols" include the combined climate-warming effects of BC (GWP=680) and the climate cooling affects of OM (GWP=−50). Error bars are the 95% CI of the mean.

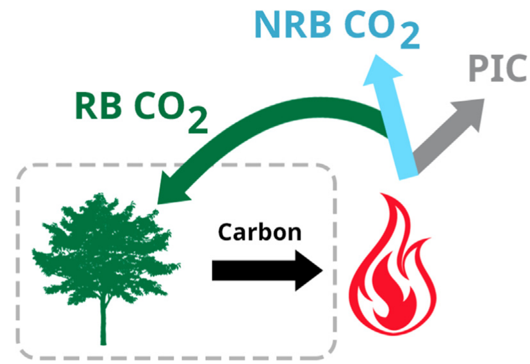

Fig. 9. Elemental carbon bound in biomass is liberated by combustion and can become either CO_2 or PICs. For sustainably harvested biomass (RB), the CO_2 emissions associated with combustion are considered to be closed-loop and do not add to the anthropogenic stock. CO_2 emissions from NRB combustion are considered to add to the anthropogenic stock. CO_2-equivalent emissions from PICs are considered to add to anthropogenic climate forcing whether they originate from RB or NRB.

by the TSF's higher contribution from gases.

The last important consideration in the analysis of the BDS's use-phase is the mix of RB vs. NRB consumed by cooking. While CO_2 emissions from RB can be considered contemporary, biospheric, and non-additional to atmospheric CO_2, CO_2 emitted by NRB is considered to be non-biospheric anthropogenic emission. In the case of RB or NRB, PICs are considered to represent additional anthropogenic climate forcing. This concept is illustrated in Fig. 9. Codipietri and Drigo (2010) demonstrated that NRB fraction varies by region in Darfur, and that the areas of highest NRB consumption occur in North Darfur near internally displaced persons camps, the same context where the BDS is being used. Assuming individuals in North Darfur will travel a maximum of 24 km from camps to gather wood, the average fraction of non-renewable biomass used for fuel is 0.55. Drigo and Codipietro's findings indicate that a large fraction of wood near IDP camps is harvested non-renewably, but it is unknown if wood transported into camps via truck comes from sources proximal to the camps (mostly NRB) or distant (mostly RB). Additional research into the sources of transported biomass would assist in providing a more accurate NRB fraction estimate. A summary of the use-phase including contributions of PIC and NRB/RB is shown in Fig. 10. In the case of 55% NRB, PICs contribution to total CO_2-e impact is 55% and 53% for the TSF and BDS, respectively.

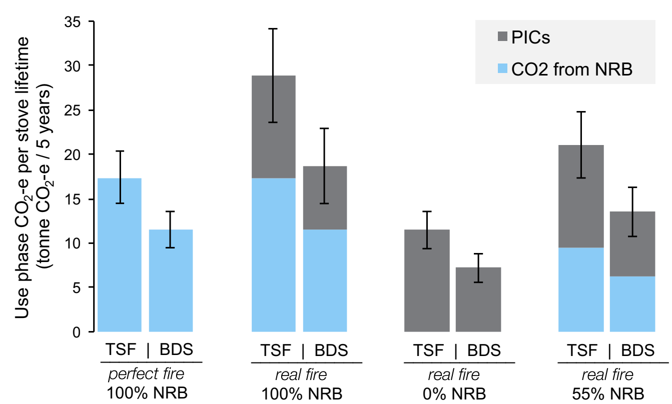

Fig. 10. This study is bounded by four use-phase emissions conditions: (1) a "perfect" fire that releases no PIC and the emissions difference is purely due to the BDS's 35% fuel savings), (2) a real fire burning 100% NRB and emitting PICs, (3) a real fire burning 100% RB, and (4) the most realistic scenario of a real fire burning the 55:45 NRB:RB ratio reported by Codipietri and Drigo (2010). Error bars are the 95% CI of the mean.

Table 3
Use data.

Metric	n	Mean	σ	SE	95% CI	
Meals per day (meals)	50	3.0	1.0	0.14	2.7	3.3
TSF wood per meal (kg/meal)	50	2.0	1.0	0.14	1.7	2.3
TSF dry wood per meal (kg/meal)		1.8		0.13	1.6	2.1
TSF dry wood use per WBT (kg/WBT)	20	0.56	0.075	0.017	0.53	0.60
BDS dry wood use per WBT (kg/WBT)	21	0.37	0.034	0.007	0.35	0.38
TSF dry wood per day (kg/day)		5.5		0.47	4.5	6.4
BDS dry wood per day (kg/day)		3.6		0.33	2.9	4.2

3.5. End of life

The end of the BDS's life comes when its components become too corroded for further use. We consider four end-of-life options: reuse, repurposing, recycling, and disposal. Not all of the BDSs parts corrode at the same rate, so some parts could be reused in new stoves, but this would require a repair and replacement infrastructure that does not exist in Darfur. Repurposing the BDS's components for other uses could be happening, but we assume that these other uses do not significantly change the global warming potential of the BDS. Recycling is an option, but the nearest steel recycling facilities are operated in Khartoum, some 1000 km away. These assumptions translate to a 0 kg CO_2-equivalent impact of the cookstove's end-of-life phase.

4. Results and discussion

Fig. 11 and Table 4 show the dramatic difference in CO_2-equivalent emissions between the use-phase and all other life cycle phases of the BDS. Regardless of NRB:RB ratio, non-use-phase CO_2-e impact is more than three orders of magnitude less than the use-phase. In the most realistic case of a 55:45 ratio of NRB to RB, the use-phase represents 850 times greater CO_2-e than all other life cycle phases combined.

Fig. 12 demonstrates the difference in five-year life cycle CO_2-e emissions between the TSF and BDS assuming a NRB:RB ratio of 55:45. Using the assumptions in this study, the BDS has a statistically significantly lower lifetime CO_2-e impact than the TSF ($p = 0.05$). The embodied emissions of the BDS associated with all non-use-phase emissions account for only 0.1% of the cookstove's life cycle emissions. Compared to the TSF, an up-front investment of 17 kg CO_2 in manufacturing and delivering the BDS to customers will mitigate approximately 7.5 tonnes of CO_2-equivalent emissions over the 5-year lifetime of the cookstove. In five years, the CO_2-e savings of the BDS vs. TSF are roughly 440 times the embodied CO_2 in the BDS.

With conservative fuel savings of 35% observed in the laboratory, one BDS will save about 4 kg of CO_2-e from entering the atmosphere per day and will pay off its embodied CO_2-e within a week of use (assuming 1:1 replacement of the TSF). At a cost of \$20 per stove and a \$0.97 per day fuel savings measured in field

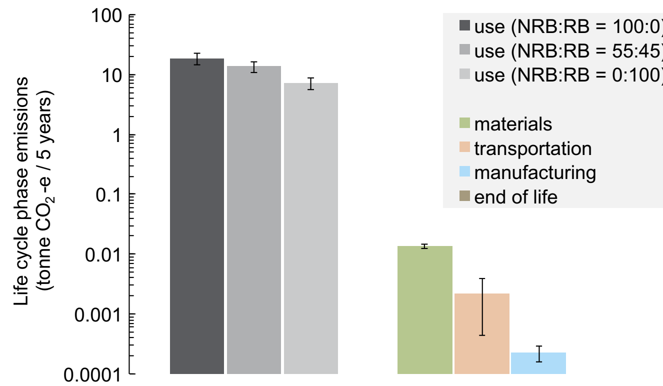

Fig. 11. Comparison of BDS emissions in all life cycle phases. Error bars for use-phase represent 95% CI of the mean while all other error bars represent conservative minimum and maximum CO_2-e impact. Note log scale.

surveys, the BDS will pay back its capital cost in three weeks of use. Hence, the BDS provides a significant economic attraction to customers while providing great potential for CO_2 mitigation.

The dominance of use-phase emissions illuminates two important insights: (1) carefully documenting and monitoring use-phase emissions must be the centerpiece for understanding a cookstove's life cycle CO_2-e impact, and (2) improving a cookstove's CO_2-e performance relies almost exclusively on improving its use-phase emissions, even if this comes at the expense of dramatically increased non-use-phase embodied CO_2-e. First, without a rigorous program to monitor use-phase emissions, an accurate claim of life cycle emissions is not possible. For example, in the case of the BDS, laboratory and field-measured fuel savings were 35% and 55%, respectively. This 20% discrepancy in fuel savings equates to a 4.2 tonne difference in predicted five-year use-phase emissions for the BDS. Similarly, uncertainties in cookstove combustion performance including CO_2-equivalent emission factors and the mix of NRB and RB have significant consequences on estimated life cycle emissions. For example, the sensitivity of the BDS's life cycle emissions to the fraction of NRB being consumed is roughly 120 kg per additional percent NRB; careful calculation of non-use-phase emissions becomes irrelevant if the NRB fraction is misjudged by just 0.2%. Therefore, given limited resources for monitoring and evaluation, an effective assessment of a cookstove's impact must be focused on the use-phase. Finally, it is critically important to understand a cookstove's emissions of products of incomplete combustion in order to accurately quantify a cookstove's use phase impact; even when burning renewable biomass, CO_2-e attributable to PICs dominate the BDS's life cycle impact. In this particular case study, Fig. 8 demonstrates that the contribution of PICs to total CO_2-e per mass of fuel burned was roughly equivalent for the TSF and BDS – hence, the contribution of PICs to life cycle emissions for the TSF and BDS scaled with their relative fuel efficiencies. In other words, the BDS reduced CO_2-e attributable to PICs, but only because of its reduced fuel use. This study used laboratory-based measurement of PIC emission factors,

Table 4
Comparison of emissions between the Berkeley–Darfur stove and a traditional three-stone fire over the course of its five-year lifetime.

Category	TSF		BDS	
	Emissions (kg CO_2-e)	± Estimated error	Emissions (kg CO_2-e)	± Estimated error
Materials	0	0	14.6	1.4
Manufacturing	0	0	0.23	0.07
Transportation	0	0	2.2	0.44
Use (NRB:RB = 55:45)	21,100	3700	13,500	2800
End of life	0	0	0	0

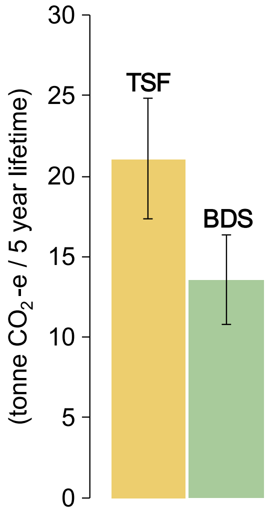

Fig. 12. Life cycle emissions over a five-year lifetime for both the BDS and TSF with 95% CI error bars assuming NRB:RB=55:45.

but measurement of a statistically meaningful quantity of in-field emissions, as exemplified in Roden et al. (2009), would be critical to quantifying a cookstove's true PIC impact.

A weakness of this study was our reliance on laboratory-based measurements of fuel consumption as a proxy for fuel savings in the field. Considering the significant dangers of field work in Darfur, we were precluded from collecting field data on fuel use. However, we fully recognize the many confounding factors influencing real-world fuel consumption such as rebound (e.g. “stove stacking”), seasonal changes, and cookstove abandonment found in other studies (Pillarisetti et al., 2014). Because we have demonstrated the importance of use-phase emissions, we recommend future researchers apply the Kitchen Performance Test, a fuel consumption standard maintained by the Global Alliance for Clean Cookstoves, in any life cycle assessment study that seeks to quantify the real-world global warming potential of a large-scale cookstove program (rather than comparing life cycle phases, as we have done here). Nevertheless, we believe that this study is a useful tool anchor for policy makers interested focusing on what matters when it comes to cookstoves and climate change, and we believe that this study will serve as a template for other cookstove researchers interested in quantifying the life cycle impacts of cookstoves.

Efforts to reduce life cycle CO_2 emissions of fuel-efficient cookstoves must focus on reductions in use-phase emissions even if those reductions come at the cost of dramatically increased emissions in other life cycle phases. Take the example of an exceptionally energy-intensive material or process added to the manufacturing of the BDS to increase its use-phase thermal efficiency. Thermal efficiency impacts BDS life cycle emissions by roughly −210 kg CO_2-e per additional percent efficiency. An energy-intensive material or process that increased BDS thermal efficiency could be justified up to an embodied CO_2-e cost of 210 kg CO_2, more than ten times the current total embodied CO_2 in the BDS. Processes that increase BDS use phase performance, almost regardless of their CO_2-e intensity, could be justified from a life cycle CO_2-e mitigation perspective. Examples of choices that could pay off include CO_2-e intensive materials, manufacturing techniques, or production locations. However, caution must be exercised when employing this line of thinking: even if per-stove emissions reductions may be attainable with more CO_2-e intensive materials or processes, the true impact of cookstoves occurs on the scale of thousands or millions of cookstoves. If technologies that reduce CO_2-e emissions make cookstoves financially unattractive, cause users to reject stoves, or influence users to operate stoves in a manner that undermines their CO_2-e mitigation potential, an increase in theoretical per-stove emissions performance becomes irrelevant.

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