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The Apeli: An Affordable, Low-Emission and Fuel-Flexible Tier 4 Advanced Biomass Cookstove

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Abstract: Based on the decision of representatives from the West African region and feedback from locals in Togo, an advanced continuous-feed, forced-draft, biomass cookstove named "Apeli" was developed. The stove was tested in modified ISO measurements based on the ISO 19867-1:2018 standard. This included a long shutdown operation using wood pellets and short shutdown operations using wood pellets, bamboo pellets, wheat straw pellets and palm kernel shells. Due to the fast shutdown capability, the short shutdown was chosen for more realistic results using this stove type. For cold start and long shutdown operation using wood pellets, the thermal efficiency is determined as 44.1% at a 1116 W power output by emitting 0.272 g CO and 17.2 mg PM 2.5 per MJ_d at high load. At low load, the efficiency is 38.0% at a 526 W power output by emitting 1.1 g CO and 45.1 mg PM 2.5 per MJ_d. Due to a misinterpretation of the standard, the burnout duration of the tests with long shutdown is approx. 1.5 min shorter than required. Using a worst-case approximation, values for a theoretical ISO-conforming measurement were calculated and rated according to the ISO 19867-3:2018 standard. The results showed that the Apeli would correspond to Tier 4 for efficiency and PM 2.5 as well as Tier 5 for CO in high-power operation using wood pellets. The use of alternative fuels is possible, but can lead to higher emissions compared to the use of wood pellets. With regard to possibly using the biochar produced in the process for soil application, it has been demonstrated that the PAH content ensures European BioChar-Agro-Organic limitations. The first results of a field test in Togo have shown that operating and feeding the stove by the target group is easy. The required permanent presence of the user during cooking with this stove seems to have a limited influence on acceptance, which seems to primarily depend on the age of the user. Moreover, it can be concluded that the Apeli has good potential to be mass-produced locally at low costs with a reliable supply of spare parts. This can contribute not only to improving clean cooking, but also to fighting air pollution and deforestation caused by solid fuel burning due to the reduced consumption of resources in the form of fuel, especially wood.

Keywords: biomass; cookstove; clean cooking; emissions; efficiency; 19867-1 standard

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1. Introduction

In 2020, about one-third of the global population (2.1 to 2.7 billion people) still had no access to clean cooking. A particular focus is on the sub-Saharan Africa region. Contrary to the global trend, the total number of people without access to clean fuels or cooking solutions continues to rise [1]. Many people, especially in developing parts of the world, have no or very limited access to modern, clean and reliable cooking facilities, despite cooking being one of the vital activities for human life. The daily exposure of family members to indoor emissions and soot particles resulting from inefficient solid fuel burning over open fires or in simple stoves has negative impacts on human health. This leads to serious health problems such as stroke, pneumonia, bronchitis, tuberculosis, asthma and lung cancer, along with higher rates of early fetal loss, preterm delivery and lower birthweight [2–5]. Particularly, newborns and infants have to spend most of their time with their mother, who is mainly responsible for cooking, and are, therefore, exposed to polluted air during the early years of their lives [6]. Indoor air pollution is the reason for the deaths of around 600,000 children younger than five years old annually [7]. There are also adverse social aspects of traditional cookstoves, such as longer cooking times, which can be used for educational or income-producing activities for women [8]. Moreover, the unsustainable use of solid fuels has serious negative impacts on the environment, such as increased deforestation due to use of 16 million ha of forests as fuel for cooking [9]. The emissions caused by incomplete combustion from biomass cookstoves contribute to 22% of global black carbon emissions and 12% of global ambient fine particulate matter (PM 2.5) [8,10].

Numerous cookstove programs and/or studies have been conducted around the world, with some still in progress, to provide cleaner cooking solutions. In this regard, it is possible to find a variety of cookstoves based on different technologies and/or fuel types, for instance: (i) wood-fueled stoves, such as the “6-brick rocket stove” (used in refugee camps in Africa) or the “VITA” stove (Ethiopia and Eritrea) [11]; (ii) charcoal-fueled stoves, such as the “Mali Charcoal” stove (Mali), the “Gyapa Charcoal” stove (Ghana) [12], the “UCODEA charcoal stove” (Uganda) and the “Lakech” stove (Ethiopia); and (iii) stoves fueled with straw and other biomass residues, such as the “TN Orient JXQ-10” (China) or the “MJ Rice Husk Gas Stove” (Indonesia) [13]. Yet, as stated in the annual report of Clean Cooking Alliance: “There’s no single stove, fuel, or business model capable of solving this complex issue” [14]. Thus, case-specific evaluation plays an important role for clean cooking solutions. In this regard, not only the needs of the communities but also technical, environmental, health, political and financial aspects can be met by taking the previously lessons learned into account.

Within the framework of the project “LabTogo”, one of the aims is to develop an advanced, low-cost and fuel-flexible biomass stove fueled with locally available agricultural/forestry residues, unlike wood- or charcoal-fueled cookstoves. Compared to other African countries such as Nigeria, Ethiopia or South Africa, Togo is a relatively small country, and biomass energy accounts for 80% of the total energy of the country [15]. Due to its increasing population, the demand of fuelwood and charcoal in Togo is increasing exponentially. However, studies show that the current potential of biomass sources in Togo is decreasing drastically, not only due to exploitation of forest sources for the production of firewood and charcoal but also due to the effects of climate change [15]. In the light of these aspects, it is important to take action toward an energy transition in the country. In this regard, the village Dévémé, located in Togo, was selected as “study field” and a field survey was carried out to understand the social and daily dynamics by focusing on cooking activities. The background information and the summary of the survey results can be found in the Supporting Information (S1). Based on the gathered feedback and the needs of the community, an advanced continuous-feed, forced-draft, biomass stove to be used in cooking applications was developed within the project.

2. Objectives

The motivation of this paper is to present the technical results from controlled laboratory experiments using a modified method of the ISO 19867-1:2018 standard [16] for the current version of the Apeli stove. The results are also compared with literature values from laboratory experiments for other stoves and which were measured according to the same standard. To the best of the authors’ knowledge, this study is one of the first in which a biomass burner for cooking applications is specifically developed and tested based on an ISO standard. It is aimed for further use in Togo and the West Africa region by considering the local needs, user comments and available biomass fuels. Therefore, the technical results presented in this paper present a valuable basis for further improvements, comparisons and applications of clean cooking.

3. Materials and Methods

3.1. The Apeli Stove

In this study, an advanced continuous-feed, forced-draft, biomass cookstove called "Apeli" (meaning "cooker which preserves the household and the environment" in the local language) given in Figure 1 was developed. The influences that led to the development of this stove are described briefly below.

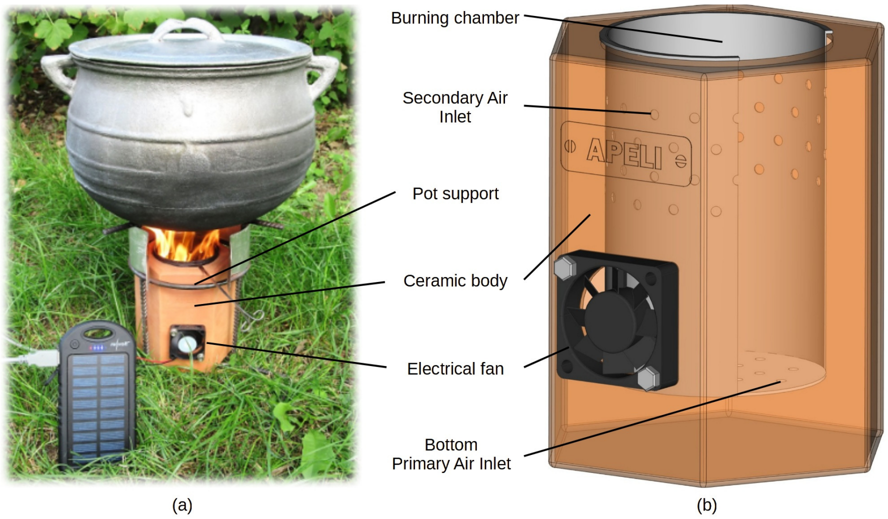


Figure 1. (**a**) Apeli stove developed by DBFZ—operating with solar power bank and typical Togolese No. 3 pot with 7 L volume; (**b**) 3D-scheme of the Apeli burner consisting of ceramic body, combustion chamber and electrical fan (cable not shown in the schematic).

Habits, traditions and preferences regarding cooking vary in different regions of the world [17]. Therefore, the stove to be developed should achieve the highest possible acceptance within the target group. Before starting development, an official meeting was held with representatives (both male and female) from different countries (Benin, Gambia, Ghana, Togo, Namibia, Niger and Nigeria) in the target region (West Africa). Some of the representatives also represented corresponding ministries of the countries of origin. In this meeting, it was also examined which basic process would have the best prospects of acceptance by the target group with regard to the respective boundary conditions. The choice was between continuously (e.g., Rocket Stove) or batch-operated (e.g., TLUD Stove) stoves. Continuously operated stoves have the advantage of a theoretically unlimited cooking time, but require the permanent presence of the user for the fuel supply. Batch stoves typically do not require the permanent presence of the user, so that the user can perform other activities in addition to cooking. However, due to the practically limited load of fuel stored in the stove, it may be necessary to interrupt the cooking process for refilling and restarting the stove, especially for long cooking times. These stoves also typically produce biochar for possible further use.

The representatives were in favor of the continuously operated stoves for the following reasons. The risk of having to interrupt the cooking process for longer cooking times in order to refill a batch-operated stove was seen by the representatives of the countries present as a major potential barrier with regard to acceptance. This potential barrier was also judged to be significantly higher than the need to constantly add fuel to continuously operated stoves. The opinion of the representatives was that users should not be forced by the process or the stove to interrupt the cooking process. The potential advantage of batch-operated stoves by producing biochar could not outweigh this potential disadvantage for the reason that biochar production was not considered a priority in this context.

Based on this main decision by the representatives and on feedback from the locals in Dévémé/Togo, as well as the local conditions such as possible production processes, available residual materials, etc., the authors have placed the main focus on the following points for stove development:

- Continuous combustion process;
- Affordable and local mass production should be possible;
- Minimization of material, specifically steel use in the stove production;
- Modular design with easy repair and spare part supply;
- High efficiency;
- Low emissions;
- Fast startup and shutdown;
- Wide power output modulation range;
- Multi-fuel capability with residual local biomasses;
- Preferably complete fuel conversion with low biochar production rate.

In this regard, the forced-air, continuous-feed updraft gasifier principle was used. The underlying combustion process is described in more detail in Section 3.2. During development, the stove was continuously tested and adapted in daily real-life cooking operation in combination with efficiency and emission measurements in the lab. The real-life cooking was performed for up to 6 persons and within a temperature range from approx. −5 to 35 °C located in Leipzig/Germany. The version of the stove described and measured in this work achieved convincing results from the authors' point of view, both in practical cooking operation and on the test bed.

To minimize the use of steel, the functions of heat generation and mechanical support are divided. The stove consists of the burner and the pot support. The pot support is formed by an exoskeleton structure made of steel rods and including a clip-on wind shield made of aluminum (see Figure 1a). The weight of the complete system (without a power source) is below 1.1 kg; ca. 550 g for the burner and ca. 500 g for the pot support.

The burner consists of three main parts: the ceramic body, the combustion chamber and the electrical fan with cable (see Figure 1b). The ceramic body has a diameter of 12 cm (edge to edge), a height of 13 cm and is produced by a molding process using liquid ceramic. This method aims to enable a fast and local mass production, considering that clay and pottery work are common practices in developing countries.

To keep the costs as low as possible, 73 × 110 mm standard cans (e.g., kidney beans, tomato paste, etc.) are used as the basis of combustion chamber construction. This part is designed as an expandable item and can be produced without the need of special tools when it has to be replaced from time to time. Due to the char gasification process with higher temperatures at the bottom of the combustion chamber, the service life of the can at this position is lower. To improve this, the combustion chamber is equipped with a bottom made of stainless steel, which can be used permanently and must be retained when changing the can-based part. Based on the construction of the combustion chamber, the ratio of secondary to primary air (defined by cross-sectional area of the holes in the combustion chamber) is fixed and amounts to 4 for pellets and 1.2 for palm kernel shells due to their special ash behavior. Palm kernel shells form ash structures during operation in this stove configuration, which reduce the primary air flow over time. This behavior is explained in more detail in Section 4.4. The geometry of the combustion chamber is described in the Supporting Information (S2). The distance between the upper edge of the combustion chamber and the upper edge of the pot support is approx. 5 cm and allows for easy fuel feeding with a spoon for the fuels used. To simplify the fuel supply as much as possible, an optimized and low-cost fuel spoon was also developed, which is mainly made of a can part (73 × 110 mm can) and a stick of wood or bamboo. The fuel supply must be replenished approximately every 60 s for wood pellets and the fuel consumption in practical use is approx. 500 g/h.

For ventilation, a standard 40 × 40 × 10 mm fan (Type: Sunon EE40100S2-1000U-999; Manufacturer: Sunonwealth Electric Machine Industry Co., Ltd.; Kaohsiung City, Taiwan) is installed and can be driven directly with 5 V DC. To drive the burner, a USB-A plug is mounted to the fan and a power bank is used as power source. The energy consumption of the stove is 0.55 W (110 mA at 5 V DC) with the fan used for the experiments. A fan control was used during development. However, this approach was discarded, since the power output of the stove can be controlled well by fuel feeding. A fan control would also cause additional costs and thus increase the retail price of the product.

The estimated retail price for the burner without a power source is estimated to be less than USD 5 and below USD 10 for the whole system (burner and pot support). This estimation is based on the production of a series with 60 stoves for field testing and using price data (i.e., material prices, labor costs, etc.) collected in 2021 during a visit to Togo. The price for a charcoal stove in Togo is about USD 10. Besides the three-stone fire, no alternative use of biomass stoves could be identified in Togo. Compared to other currently produced advanced stoves, such as the Mimi Moto with a price of ca. USD 100 or the ACE 1 with a price of ca. USD 89 [10], this is much cheaper.

An analysis of environmental and climate impacts in Togo [18] based on the results during the development process has shown that even a small substitution rate (5%) of traditional or charcoal stoves by the Apeli will have a big impact regarding wood saving and CO_2 emissions. For a small country such as Togo, the reduction in both would be in the order of 100,000 metric tons.

3.2. Combustion Process

Due to the constraint of using a continuous process with the highest possible efficiency and low emissions, modern pellet boilers and stoves for domestic heating were used as a technical starting point for stove development. These meet the requirements with the technology they use and comply with the high air pollution control requirements in Europe and North America. Examples of this are boilers such as the Guntamatic Biostar, the Windhager BioWin2 or the Fröhling PE1. A brief introduction for this boiler type, including an example illustration, is given in the Supporting Information (S3).

Within this selected process, the fuel is completely burned in two spatially separated steps. In the first step, the biomass is converted with primary air into syngas. This takes place inside the fixed bed of the combustion chamber where char gasification and biomass pyrolysis take place. The syngas is burned with secondary air at the second step with low emissions. In the Apeli's design, due to this process and on the contrary to typical Top Lit Up-Draft (TLUD) biomass-fueled cookstoves, a continuous feed of fuel during the process is possible in addition to char gasification, which enables a more feasible process. Moreover, stoves with smaller dimensions can be produced, since it is not necessary to store the fuel in the stove for an entire cooking cycle.

As shown with the pellet boilers, the thermal power output of the Apeli is also adjustable by changing the fuel feeding rate and depends in addition on the fuel itself. However, in addition to the advantages of this technology, the disadvantages must also be accepted. These include, in particular, fuel selectivity with regard to the ash melting point due to the high temperatures in the firebed, which can lead to slagging [19].

Usually, in the aforementioned boiler systems, the combustion chambers are dimensioned so that the combustion reaction can be completed without touching cooler objects. In cookstoves, the cooking pot is usually located just above the combustion chamber. To prevent direct contact of the flame with the cooking pot as much as possible, the combustion chamber's geometry was adapted so that the flame is rather short. Together with the distance needed to feed the stove, direct contact of the flame with the pot can thus be almost entirely ruled out when the stove is operated correctly.

Figure 2 shows a schematic of the observed process in the combustion chamber of the Apeli. The active reaction zone for char gasification and pyrolysis has a height of just approx. 1–1.5 cm and allows the secondary air openings to be deeply integrated and widely distributed in the combustion chamber. This also enabled the formation of a hot gas jet, which flows from the center of the combustion chamber from below against the bottom of the pot. If flames reach the bottom of the pot, they will only emanate from the rim area of the combustion chamber when operated correctly. The authors assume that the hot gas jet forms a protective layer between the bottom of the pot and the flames, which prevents direct contact and is also primarily responsible for the low emissions of the stove. Further tests and CFD simulations are planned in this regard to further test this assumption.

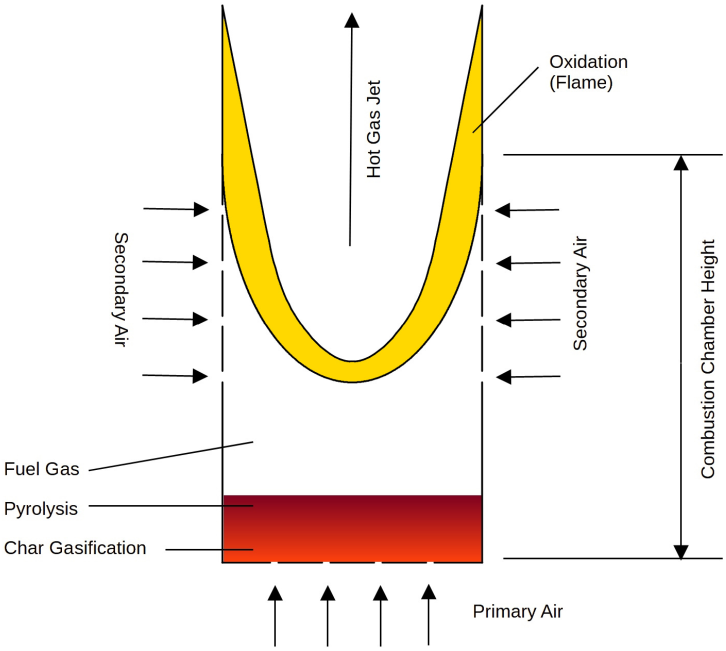


Figure 2. Graphical representation of the combustion process observed during the development and measurements of the Apeli stove.

Furthermore, the combustion chamber geometry shown allows the stable combustion of the gases from char gasification during burnout. This also leads to low CO emissions in this phase and supports quick and easy reignition if needed for the cooking process.

3.3. Biomasses

Four different biomasses were used for the tests, three types of 6 mm pellets and palm kernel shells (sieved with a 5 mm round hole sieve). Wood pellets (WP) were used as a reference fuel to compare the results with other biomass stoves. Palm kernel shells (PK) and bamboo pellets (BP) were selected as locally available fuels. Wheat straw pellets (SP) were selected as reference fuel with high ash and potassium content, as well as a low ash melting temperature as "worst case fuel". The fuel specifications are given in Table 1 in addition to their photos in Figure 3.

Table 1. Fuel specifications of the biomasses used in cooking experiments (* db, wt.%).

Parameter	**Standard**	**WP**	**BP**	**SP**	**PK**
Moisture (ar **)	EN ISO 18134	7.5	7.7	8.3	11.1
Ash (550 °C)	EN ISO 18122	0.3	1.8	8.43	2.2
LHV (MJ/kg)	EN ISO 18125	19.06	18.68	16.65	19.74
C	EN ISO 16948	51.2	48.6	45.0	52.3
H	EN ISO 16948	6.28	5.19	6.04	5.59
N	EN ISO 16948	0.12	0.30	1.82	0.32
S	EN ISO 16948	0.08	§ n.d.	0.14	§ n.d.
O (by difference)		42.02	44.11	38.57	39.59
K (mg/kg) *	EN ISO 16967	444	4090	10900	898
Ca (mg/kg) *	EN ISO 16967	861	748	4190	669

*—db (dry basis); ar **—as received; § n.d.—not determined; WP—wood pellets; BP—bamboo pellets; SP—wheat straw pellets; PK—palm kernel shells.

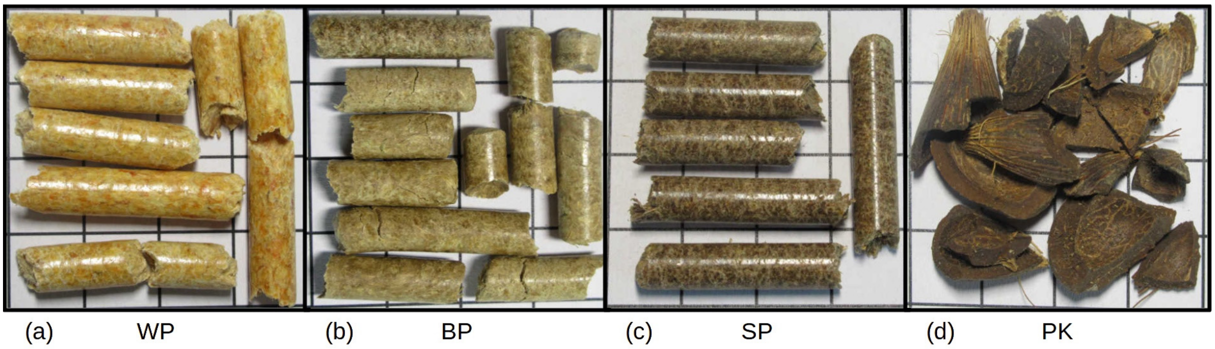


Figure 3. Fuels used in the experiments; (**a**) Wood pellets; (**b**) Bamboo pellets; (**c**) Wheat straw pellets; (**d**) Palm kernel shells; edge length of a box is 1 cm.

3.4. Cooking Pot

A Togolese No. 3 pot was used for the experiments. It is a round bottom pot made of aluminum (approx. 5 mm thickness) with the approximate dimensions of 18 cm height and 27 cm diameter. The mass of the vessel is 1459 g without the lid (according to the standard). Its full capacity is approximately 7 L, and the pot is used with 5 L of water for the tests.

3.5. Combustion Test Procedures

The combustion tests were performed as modified ISO measurements based on the ISO 19867-1:2018 [16] standard. Measurements using the long shutdown operation, which are close to the specified test cycle of the standard, offer the possibility of determining comparative values such as thermal power output, thermal efficiency and pollutant metrics as objectively as possible.

For the assignment of the results, an identifier is used according to the fuel–power–shutdown pattern for the experiments in this publication. The experimental matrix is shown in Table 2.

Table 2. Experimental matrix for modified ISO measurements using different fuels, loads and stopping criteria in addition to data from other studies for comparison; stove shutdown criteria are explained in Section 3.5.1 (long) and Section 3.5.2 (short)—ISO: according to ISO 19867-1:2018 [16]; * approximate shutdown duration was reconstructed using the measured CO values as an indicator.

Study Identifier	Stove	Fuel	Power Range	Stove Shutdown	Shutdown Duration * [s]	Number of Replicates	Source
WP-H-L	Apeli	WP	High	Long	211 ± 29	5	This study
WP-L-L	Apeli	WP	Low	Long	213 ± 87	5	This study
WP-H-S	Apeli	WP	High	Short	21 ± 4	3	This study
BP-H-S	Apeli	BP	High	Short	8 ± 7	3	This study
SP-H-S	Apeli	SP	High	Short	10 ± 3	3	This study
PK-H-S	Apeli	PK	High	Short	16 ± 9	3	This study
MM	Mimi Moto	Hardwood Pellets	High	ISO	-	7	Champion et al. [10]
PH	Philips HD4012	Cut Red Oak	High	ISO	-	7	Champion et al. [10]

3.5.1. Test Cycle with Long Shutdown Phase

The combustion chamber of the cold stove was filled with one layer of fuel. At the start, a wood wool wax igniter was ignited, and the measurement devices were turned on. The burning igniter was placed in the middle of the combustion chamber and the fan was started immediately. Afterwards, additional fuel was filled around the igniter until it had the same height (approx. 2.5 cm). Following that, the cooking pot was placed. Both the water temperature at the start of the experiment and the ambient temperature were 20 ± 2 °C. From this point on, fuel was added continuously so that the flames did not touch the bottom of the pot if possible. The frequency and mass of fuel per feed are especially crucial for combustion. This varies for each fuel and must be practiced for optimal results. For the best possible comparison between the fuels, the last fuel feed was performed at the end of the 30 min fuel burning period. After this point, the stove changes to char gasification within a short time. The measurement was finished after 35 min. The energy content of the igniter is also considered in the calculation, which was based on ISO 19867-1:2018 [16]. A measurement series consists of five experiments.

For the experiments, low load is defined by the existence of a small, stable flame of pyrolysis gases in the combustion chamber. For that reason, the values for the low load test (WP-L-L) should be seen more or less as an additional information for better classification.

According to the ISO 19867-1:2018 [16] standard, the following two termination criteria apply: (1) the water temperature drops 5 K or (2) the measurements ends 5 min after the fuel burning period. Due to the fact that the last fuel feed took place after 30 min and the measurement was completed after 35 min, the waiting time after the fuel burning period is with approx. 3.5 min shorter than the 5 min required by the standard. For that reason, the measurements were conducted based on and not strictly according to the standard and are thus classified as modified ISO.

The geometry of the combustion chamber ensures that the gases from the char gasification period are also burned with as few emissions as possible. Nevertheless, the CO values in this phase are higher than in the fuel burning period. Due to the shortened waiting time compared to the standard, the CO values determined in this work are lower than they would be if measured according to the ISO 19867-1:2018 [16] standard. For the approximation of emission values for a theoretical ISO-conforming measurement, a worst-case scenario was used in Section 4.3, and the results were classified according ISO 19867-3:2018 [20].

For comparison of the results from the Apeli using WP with a long shutdown and a high-power output (WP-H-L), two biomass stoves (the Philips HD4012 [10] and the Mimi Moto [10]) were chosen from the literature due to their high thermal efficiency and low-emission operation. Moreover, these stoves are in roughly the same performance class. The Philips HD4012 is no longer sold on the market, but has been replaced by the technically identical and rebranded ACE 1 [10]. Both stoves are gasifier stoves and use the TLUD principle. Regarding the parameters of the stoves mentioned, the Mimi Moto has the best parameters and can be considered state-of-the-art.

3.5.2. Test Cycle with Short Shutdown Phase

The Apeli stove has a fast shutdown capability. For this reason, there is no need for long waiting times after the fuel burning period in practice. To generate values closer to real-life operation, the experiments were stopped instantly after the fuel burning period and when the char gasification started in this mode. Since the burnout phase was nearly completely cut out, these measurements are not in line with the ISO 19867-1:2018 [16] standard.

3.5.3. Biochar Analysis

In the context of soil application, the use of biochar compost can significantly improve crop yields in most tropical soils, especially for dry or saline soils [21]. The Apeli produces small amounts of biochar during its operation. In order to test the possible use of the produced biochar in soil improvement, the produced char was tested for the PAH content. Due to the small amounts of biochar produced by the stove, for PAH analysis, a mixed sample of every measurement series with 3 or 5 experiments was carried out and analyzed (1 ± 0.03 g per experiment). The samples were analyzed by Eurofins Umwelt Ost GmbH in Freiberg/Germany.

3.6. Measurements

The Apeli was tested within the DBFZ laboratories for thermochemical conversion in the city of Leipzig, Germany. A schematic of the test bed is given in the Supporting Information (S4). The measurement set-up was prepared according to ISO 19867-1:2018 [16] by ensuring the requirements of the standard were met.

The measurement devices used for the experiments are listed in Table 3 and fulfill the requirements of ISO 19867-1:2018 [16]. The CO content in the flue gas was measured according to EN 15058:2017 [22]. In addition to the calibration of the gas analyzer with certified calibration gas and due to the low levels of CO in the flue gas, calibration was also carried out with N_2 5.0 as a zero-point gas with a purity of min. 99.999% according to ISO 14175:2008 [23]. The particle measurement in the flue gas was performed based on EN 13284-1:2017 [24].

Table 3. Measurement devices used in the experiments.

Designation	Model
Gas analyzer	Horiba PG-350E * (Horiba Ltd.; Kyoto, Japan)
Particle Measurement	Particle measuring system ITES (Paul Gothe GmbH; Bochum, Germany) Cascade impactor Johnas (Paul Gothe GmbH; Bochum, Germany) Fiber filters MK 360 (Munktell Ahlstrom)
Data Logger	Almemo 710 (Ahlborn; Holzkirchen, Germany)
Sensors temperature	Type K thermocouple with Almemo Plug (Ahlborn)
Sensor gas velocity	Thermo-anemometer FVAD 05 (Ahlborn)

* Measuring principles: NDIR for CO.

4. Results and Discussion

In addition to presenting the results from the experiments, the authors would like to give additional comments regarding the ISO 19867-1:2018 [16] standard based on observations made during the tests. Additional data are given in the Supporting Information (S5).

4.1. Thermal Power Output and Efficiency

The thermal power output values are given in Table 4. In the tests with a long shutdown time, the measured turndown ratio was approx. 2.1 and the power output ranged from 526 to 1114 W. For short shutdown tests, the power output was in the order of BP ≈ PK > WP >> SP and ranged from 884 to 1199 W. When using SP, it is noticeable that this fuel has a lower performance in the stove compared to the other fuels. The thermal power output is not an evaluation criterion within the framework of the standard and is shown for classification of the power class.

Table 4. Thermal power output of the Apeli stove.

Study Identifier	Thermal Power Output (W)
WP-H-L	1116 ± 89
WP-L-L	526 ± 33
WP-H-S	1094 ± 50
BP-H-S	1199 ± 27
SP-H-S	884 ± 35
PK-H-S	1194 ± 21

Moreover, the efficiencies are shown in Figure 4. The efficiency values presented consider char credit and are determined as a factor that combines the energy delivered to the cooking water with the fuel energy used. The (theoretically) still usable energy from the char produced in the process is deducted from the fuel energy.

As can be seen, the thermal efficiency for all experiments with high power output is higher than 40%. The experiment using WP and a short shutdown (WP-H-S) has a lower efficiency than the experiment with WP and a long shutdown (WP-H-L). This was unexpected for the authors, since WP-H-S is finished directly when the pyrolysis of the last added fuel finishes and the char gasification starts. This phenomenon is discussed in Section 4.5.1. Using a short shutdown time, WPs have the lowest thermal efficiency compared to the other fuels used. In low loads (WP-L-L), the Apeli falls below 40% efficiency. In comparison to both reference stoves, the efficiency of the Apeli in high loads

(WP-H-L) is higher than the Philips HD4012 and in the same range as the Mimi Moto. It should also be mentioned that the Mimi Moto has several combustion chambers and the thermal efficiency varies with the change in combustion chambers [10]. Thus, the thermal efficiency of the Mimi Moto could be higher with comparable power output (in W) to the Apeli.

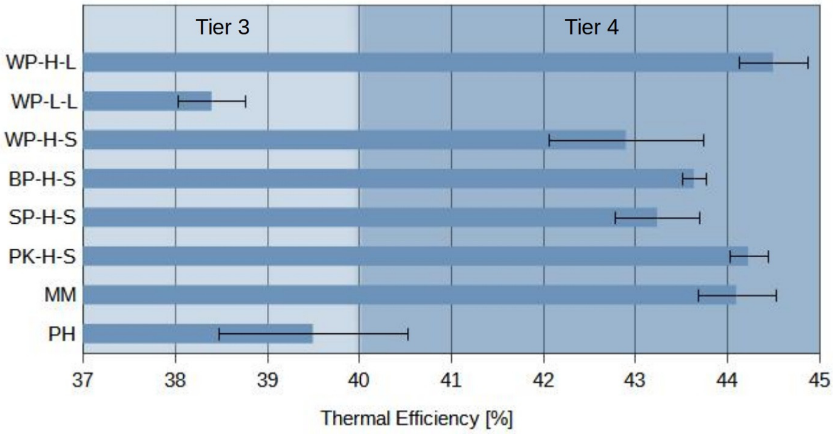


Figure 4. Thermal efficiency of the Apeli stove in comparison with the Philips HD4012 [10] and Mimi Moto [10] stoves at high power output. Confidence intervals (90%), as specified in ISO 19867-1 [16], using pooled standard deviations are represented by the error bars.

4.2. Emissions

The emissions based on the delivered amount of energy, as shown in Figure 5, depend on the fuel type and selected load. The lowest overall emissions, CO and PM 2.5 could be observed in the WP-H-S test. However, the measurements from WP-H-L and PK-H-S are close to that result. For high loads, the CO emissions for all measurements are below 0.5 g/MJ$_d$. For low loads and long shutdown times using WP, the CO emissions are higher and slightly above 1 g/MJ$_d$. The PM 2.5 emissions for using WP and PK in high loads (short and long shutdowns) are close and within the range of 15.1 to 17.2 mg/MJ$_d$. By using BP, the measured PM emissions (30.9 mg/MJ$_d$) are twice as high compared to WP; using SP (87.7 mg/MJ$_d$), they are over five times as high. In comparison with the reference stoves, the CO and PM 2.5 emissions of the Apeli using wood pellets (WP-H-L) are clearly lower than the Mimi Moto and the Philips HD4012.

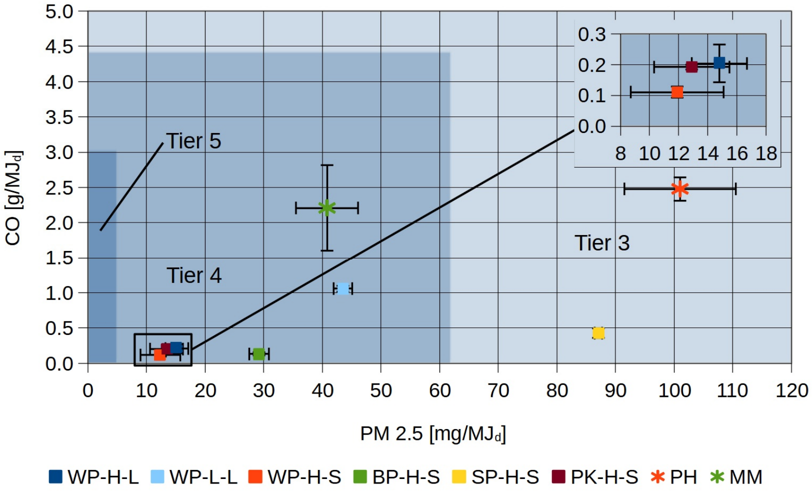


Figure 5. Emissions of the Apeli stove in comparison with the Philips HD4012 [10] and Mimi Moto [10] stoves at high power output. Confidence intervals (90%), as specified in ISO 19867-1 [16], using pooled standard deviations are represented by the error bars.

The results of the indoor emissions, as shown in Figure 6, are close to the emissions based on the delivered amount of energy in Figure 5. Again, the emissions with short shutdown times using WP are lower than the measurements with long shutdown times. In addition, the behaviors are the same for PK, BP and SP. However, the emissions using low loads are closer to the emissions when using high loads. The results show that the emission values using WP and PK as fuels are close. BP causes higher PM 2.5 emissions and SP has increased PM 2.5 and CO emissions. In comparison to the reference stoves, the Apeli using WP (WP-H-L) has the lowest CO and PM 2.5 emissions. However, since this category looks at emissions over time, stoves with less power output have an advantage over stoves with higher power output and the same emission factors based on the delivered amount of energy.

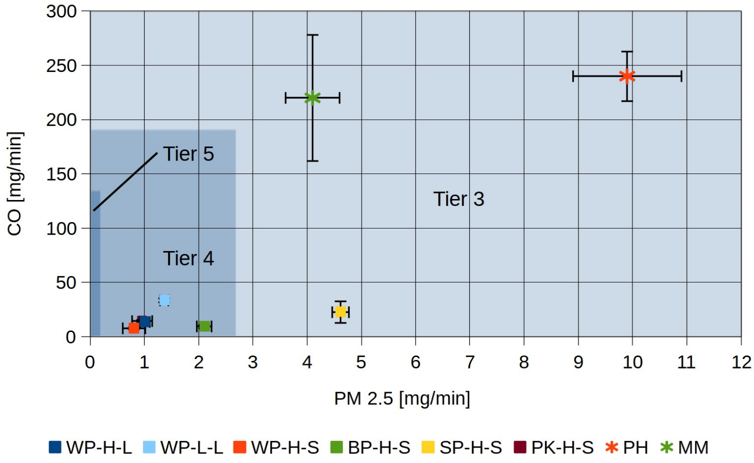


Figure 6. Indoor emissions of the Apeli stove in comparison with the Philips HD4012 [10] and Mimi Moto [10] stoves at high power output. Confidence intervals (90%), as specified in ISO 19867-1 [16], using pooled standard deviations are represented by the error bars; PK-H-S is behind WP-H-L.

Figure 7 shows the loaded filter for PM 2.5 measurements. The PM from the Apeli looks different based on the fuel used and ranges optically from dark carbon-rich soot (Figure 7a,d) to a composition without visible black carbon and a very light color (Figure 7c). The chemical composition of the particles was not examined within this work. The PM generated by burning the different fuels also seems to be related to the content of potassium and calcium (see Table 1). Generally, PM from forced draft cookstoves consists mostly of inorganic substances [25], and the mutagenicity of these emitted particles depends on the combustion quality (stove model) as well as the used fuel and is correlated with the PAH content [26]. For a rocket stove, it could be shown that the particles generated by using straw are smaller and have a higher toxicity per mass compared to the use of wood [27]. Especially regarding the toxicity and mutagenicity, a further examination for the size, composition and PAH content of the particles should be conducted in the future. In addition to the technical challenges with ash- and potassium-rich fuels, this could be crucial for the possible use of these fuels in the stove regarding health aspects.

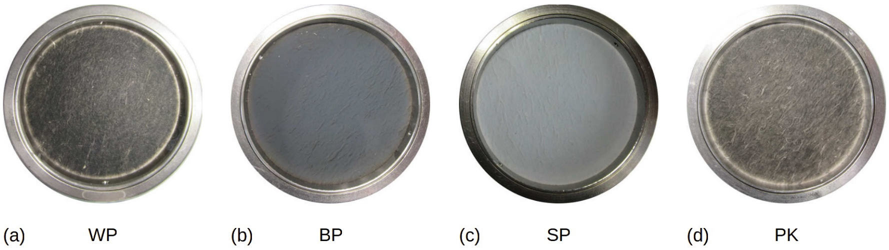


Figure 7. Filter for particle measurements (PM 2.5) after the experiments for the fuels used; (**a**) Wood pellets; (**b**) Bamboo pellets; (**c**) Wheat straw pellets; (**d**) Palm kernel shells.

4.3. Approximation of Measurement Values According to ISO 19867-1:2018 and Classification According to ISO 19867-3:2018

The main limitation of this study regarding the measurements is the fact that, due to misinterpretation, the length of the burnout, even for the long shutdown mode, is just approx. 3.5 min compared to the 5 min prescribed in the ISO 19867-1:2018 [16] standard. For this reason, the collected measurement results cannot be used directly to classify the stove according to ISO 19867-3:2018 [20], although they are certainly in the ranges for Tier 4 (efficiency and PM 2.5) or Tier 5 (CO). The comparison of measurements with short (WP-H-S) and long shutdown (WP-H-L) times using wood pellets shows that with the increasing length of burnout, all three parameters increase—efficiency, PM 2.5 and CO. While this is not critical in the case of efficiency, increasing emission values could cause the rating to deteriorate. In the case of emissions, it can be seen that the PM 2.5 values correlate only slightly with the burnout duration, but that there is a strong dependence in the case of CO values. In order to be able to make a preliminary classification according to ISO 19867-3:2018 [20] within the scope of this study until our own new ISO-compliant measurement results or those of another party become available, the emission values are approximated for a theoretical ISO-compliant measurement.

For the estimation, a linear extrapolation is used taking the emission values and times of the short (E_S, t_S) and long (E_L, t_L) shutdown modes, which is shown in formula 1. In order to make a worst-case estimation and to generate the highest possible values for the theoretical measurement according to the available data, the following values are used as input parameters. For the emission values, the upper boundary of the 90% CI (mean + 90% CI) is used. With regard to the determined burnout durations (see Table 2), the minimum duration for the long burnout (t_L = 189 s) and the maximum duration for the short burnout (t_S = 25) are used in order to maximize the generated emission value, E_{eISO}:

$$E_{eISO} = (E_L - E_S)\frac{300s - t_S}{t_L - t_S} + E_S \tag{1}$$

The calculated emission values (E_{eISO}), as well as the input parameters and limits according to ISO 19867-3:2018 [20] for Tier 4 and Tier 5 classification, are shown in Table 5.

Table 5. Emission limits according to ISO 19867-3:2018 [20], input and output values for approximation of a theoretical ISO-compliant measurement.

	PM 2.5		**CO**	
	mg/MJ$_d$	**mg/Min**	**g/MJ$_d$**	**mg/Min**
Tier 4 Limits	62.0	2.700	4.400	190.0
Tier 5 Limits	5.0	0.200	3.000	133.0
E_S (WP-H-S)	15.8	1.005	0.135	8.5
E_L (WP-H-L)	17.2	1.103	0.272	16.7
E_{eISO}	18.3	1.177	0.375	22.9

It can be seen that according to the chosen approximation method, all emission values for a theoretical ISO-compliant measurement (E_{eISO}) are higher than the values with long burnout phase (E_L), as expected. Compared to the experiments with long shutdown times and high load, the PM 2.5 emission values are approx. 7% higher and the CO values are approx. 38% higher. In order to reach the limit values of the corresponding Tier (Tier 4 for PM 2.5 and Tier 5 for CO), the values for PM 2.5 would have to increase by at least another 129% and those for CO by at least 580%. In view of these values, the authors consider it very unlikely that the corresponding emission parameters will exceed these limits if the burnout period is extended by 1.5 min for an ISO-compliant measurement. Furthermore, the approximated values do not change the comparison to the Philips HD4012 and Mimi Moto stoves. A new value for efficiency was not calculated, as this would be higher in the approximation compared to the long shutdown mode and is not a risk in terms of classification.

For these reasons, the authors classify the developed Apeli stove using wood pellets and pending ISO-compliant measurements, as shown in Table 6. Since at least Tier 4 is achieved for all sub-tiers, the Apeli is classified as a Tier 4 stove.

Table 6. Classification of the corresponding parameters according to ISO 19867-3:2018 [20].

Metric	Unit	Sub-Tier
Thermal efficiency with char credit	%	Tier 4
PM 2.5 per useful energy	mg/MJ_d	Tier 4
CO per useful energy	g/MJ_d	Tier 5
PM 2.5 emission rate	mg/min	Tier 4
CO emission rate	mg/min	Tier 5

4.4. Biochar and Ash Formation

The remaining biochar produced by the Apeli is shown in Figure 8. The carbon sequestration rate of the Apeli is low compared to TLUD stoves due to the different combustion processes and ranges for short shutdown experiments with different fuels from 10.3% to 14.8% (BP < WP < SP < PK). For the experiments with WP and a long shutdown time, the rate was 8.7% for high load and 5.7% for low load.

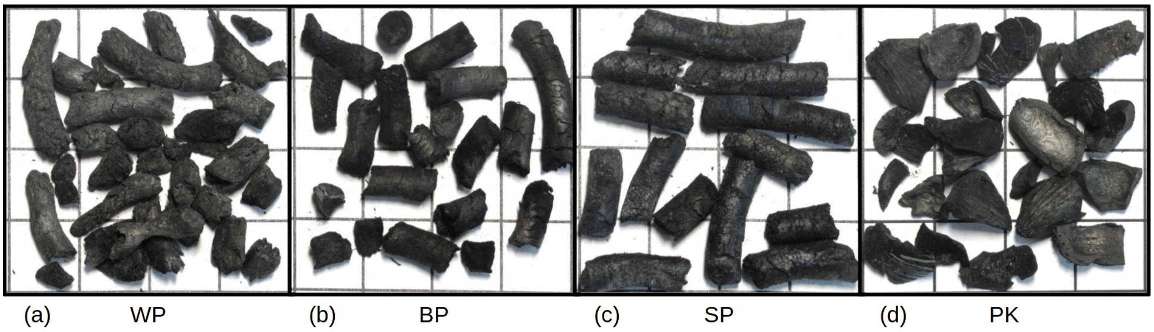


Figure 8. Produced biochar samples of the used fuels; (**a**) Wood pellets; (**b**) Bamboo pellets; (**c**) Wheat straw pellets; (**d**) Palm kernel shells; edge length of a box is 1 cm.

To check the suitability of the produced biochar regarding a possible soil application, the PAH content was analyzed based on the European Biochar Certificate (EBC) [28], and the results are shown in Figure 9. For all fuels, the amount of PAH was within the range for organic farming. PK had the highest PAH value and were close to the limit for regular farming.

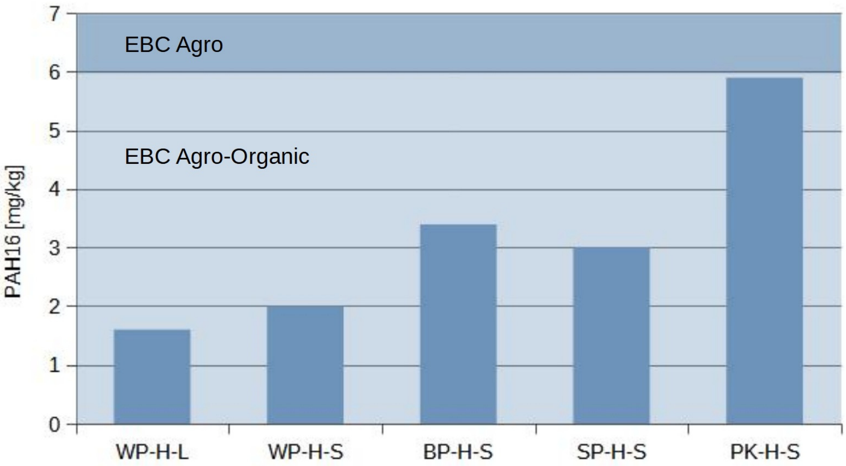
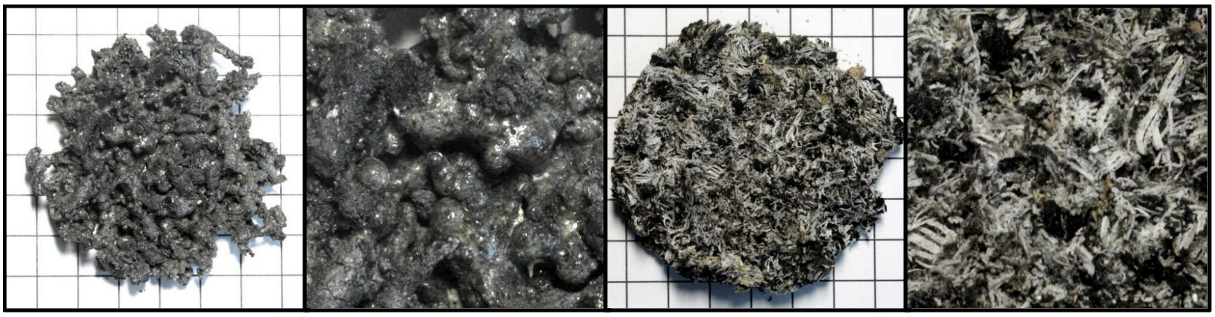


Figure 9. PAH16 content of the produced biochar by the Apeli stove.

Due to the char gasification, the temperatures within the char bed can exceed the ash melting point for some fuels. Especially for fuels with a high ash content, this process can present a challenge in real world operation. During several tests, it was observed that two fuels (PK and SP) had a special ash behavior. Both began to form an ash cake with different characteristics. For WP and BP, such ash behavior was not observed.

SP formed a molten structure with high density and large pores (Figure 10a), which also allowed sufficient primary air to flow through. For that reason, there was no negative impact to the power output over time or regarding the handling of the stove. Due to the high ash content of SP, the accumulating ash mass could reach a critical level after a longer period of cooking. The critical level could be that the primary reaction zone is lifted by the ash cake, reaches the secondary air openings and impedes the combustion process. SP was not used as fuel for real cooking tests during development in order to gain further knowledge. In general, the ash behavior shown for straw-based fuels in pellet heating systems [19] and in laboratory tests on ash melting behavior [29] is well known and was expected.


(a) SP

(b) PK

Figure 10. Ash formation within the process; (**a**) Wheat straw pellets; (**b**) Palm kernel shells; edge length of a box is 1 cm.

PK formed a very delicate felt-like structure of fine needles with low density (Figure 10b). Although the fuel has a low ash content, the felt-like structure reduces the primary air flow over time by closing the primary air openings, and a de-ashing of the combustion chamber is necessary after 35 to 40 min of cooking. A small workaround for de-ashing and reigniting fresh fuel by using the hot char formed was tested successfully during real cooking tests. For this purpose, the hot char was poured onto a tray and the ash was disposed of. The glowing char was then poured back into the combustion chamber and the burner reignited with fresh fuel. This process took about 30 s. The ash behavior of PK shown was not expected by the authors, and no literature could be found that shows comparable behavior.

Another problem with the buildup of ash structures could be the altered airflow within the combustion chamber, thus redirecting the flow of hot gas flow from the char bed to the wall of the combustion chamber. This could have a negative impact on the life time of the combustion chamber, and additional protection in that high-temperature region could be required.

4.5. Comments Regarding the ISO 19867-1:2018 Standard

The ISO 19867-1:2018 [16] standard is intended to ensure "comparability in measurement of cookstove emissions and efficiency". During the measurements based on the standard and the comparison of our own results with values in the literature, the authors of this study noticed two points within the methodology of the standard which could be optimized regarding the calculation of the useful energy delivered. We would like to discuss these points in order to improve the comparability of measurement results from different sources and with regard to the further development of the standard.

4.5.1. Temporal Linkage of Water Temperature and Water Mass Measurement to Calculate the Useful Energy Delivered

For the calculation of the useful energy delivered, the highest measured water temperature and the mass difference of the water are used. These values are not collected at the same time and are therefore decoupled in time. The authors suspect that this leads generally to increased calculated efficiency and reduced emission values, which probably do not exist in practice. For these hypotheses, the authors rely on their own measurements and calculations, which are presented briefly in the Supporting Information (S6).

For this reason, the authors propose to use both the water temperature as well as the water mass at the end of the experiment as the basis for calculating the useful energy delivered.

4.5.2. Inclusion of the Thermal Mass of the Pot to Calculate the Useful Energy Delivered

The heat capacity and evaporation of the water are used as the basis for calculating the useful energy delivered. Since the thermal mass of the pot is not integrated into the calculation, this can lead to significant deviations in the calculated efficiency and emission values for very different pots. Moreover, it can hinder the comparison of literature values. The authors have explained this influence with an example briefly in the Supporting Information (S7).

For this reason, the authors propose to think about integrating the pot into the heat balance for calculation of the useful energy delivered.

5. Conclusions

Based on the decision of representatives from West Africa region and feedbacks from locals in the village Dévémé, the advanced continuous-feed, forced-draft, biomass stove “Apeli” was developed with the focus of local and affordable mass production in Togo and providing high efficiency and low emissions using locally available fuels.

Lab tests with short and long shutdown were performed based on ISO 19867-1:2018. The tests with long shutdown were performed as a comparative reference and the short shutdown as a more realistic stove operation. Due to a misinterpretation of the standard, the burnout duration of the test is not in line with the standard (approx. 3.5 min vs. 5 min). For this reason, all measurements performed in this work are classified as modified ISO. The Apeli’s test results were also compared with those two other stoves on the market, the Mimi Moto and the Philips HD4012 (rebranded as ACE 1). In the reference operation with high load and long burnout using wood pellets, it was shown that the PM 2.5 and CO values are lower than those of the Mimi Moto and Philips HD2012 stoves selected for comparison. The thermal efficiency was higher than the Philips HD4012 and in the same range as the Mimi Moto. For low load and long shutdown, PM 2.5 as well as CO emissions are higher, accompanied by lower efficiency. The tests with short shutdown and high load using different fuels have shown that especially the PM 2.5 emissions are dependent on the fuel used. Regarding CO emissions, only straw pellets resulted in clearly higher values.

Since the measurements performed do not meet the required burnout duration of the standard, values for a theoretical ISO-compliant measurement at high load using wood pellets were calculated in a worst-case approximation. It was found that the calculated values are far enough away from any limit values and allow for classification according to ISO 19867-3:2018 with low risk. The classifications showed that the Apeli would meet Tier 4 limits for efficiency as well as PM 2.5 and Tier 5 for CO. Since all sub-tiers are at least Tier 4, the Apeli was classified as a Tier 4 stove overall.

The produced biochar in the process was tested for PAH with regards to possible use for soil application. The tests have shown that the PAH content is low and the biochar fulfils the criteria for organic farming according to the European Biochar guideline.

In June 2022, 56 stoves with spare parts were delivered to Togo for field tests, teaching activities and scientific experiments at the university. A field test is in progress, and based on the first round of user feedback, it is possible to say that the operation and feeding of the stove is easy. The constant presence of the user seems to have a subordinate influence on acceptance. Initial findings showed that acceptance is probably significantly influenced by the age of the user. Younger people are using the stove extensively, while older users tend to stick to traditional cooking fires. In general, it can be said that the decision of use is made at the beginning. Users who have started using the stove still do so months later. In the future, small adjustments can be made to the pot support based on user feedback. For additional potential fuels, the combustion chamber might need to be adapted. Apart from this, it is planned to integrate Apeli burners in traditional fireplaces as a replacement of the fire to further increase acceptance and lower the acquisition price of the system.

Based on the observation of a hot gas jet during development and testing, further investigations and CFD simulations are planned in this area. These are intended to further improve emissions and efficiency and deepen our understanding of the process used.

In general, urgent action is needed to achieve clean cooking with fuel-saving technologies in developing countries, especially considering the health and environmental aspects. However, price is still a limiting factor for the widespread dissemination of such technologies. The Apeli, with good technical parameters and low estimated costs in mass production, shows great potential to change the situation in these regions sustainably.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16073278/s1, Figure S1: Traditional stove used in Dévémé/Togo; Figure S2: Geometry of the combustion chamber; Figure S3: 3D-Schematic of pellet stove type using a burner cup and fuel dropping system; Figure S4: Schematic of the test bed; Table S1: Detailed data of the experiments WP-H-L; Table S2: Detailed data of the experiments WP-L-L; Table S3: Detailed data of the experiments WP-H-S; Table S4: Detailed data of the experiments BP-H-S; Table S5: Detailed data of the experiments SP-H-S; Table S6: Detailed data of the experiments PK-H-S; Table S7: Estimated thermal efficiency for burnout phase; Table S8: Comparison of thermal efficiencies using different water temperatures as input parameters; Table S9: Comparison of thermal efficiencies using different pot parameter. References [30–34] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, D.K.; methodology, D.K.; validation, D.K. and Ö.M.; formal analysis, D.K.; investigation, D.K. and Ö.M.; resources, D.K.; data curation, D.K.; writing—original draft preparation, D.K. and Ö.M.; writing—review and editing, D.K. and Ö.M.; visualization, D.K.; supervision, D.K.; project administration, D.K.; funding acquisition, D.K. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

BP	Bamboo Pellets
CCT	Controlled Cooking Test
CFD	Computational Fluid Dynamics
GDP	Gross Domestic Product
ICS	Improved Cookstove
ISO	International Standard Organization
KPT	Kitchen Performance Test
PCIA	Partnership for Clean Indoor Air
PK	Palm Kernel Shells
PM	Particulate Matter
TLUD	Top Lit Up-Draft
WBT	Water Boiling Test
WHO	World Health Organization
WP	Wood Pellets
SP	Wheat Straw Pellets

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