A comprehensive review on small-scale combustion technologies in Southern Africa, what is known, done and emergent knowledge gaps?

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Abstract— This is a review paper written with the intention to shed light on continued reliance on high polluting energy sources in the Southern Africa. In developing countries the use of low cost fuels including coal, wood, pellets, charcoal and cow dung remains an obstacle in ensuring the right to clean air. In this study, several stove to fuel combustion technologies researches, were reviewed for similarities/ commonalities and differences. The review highlights on critical health and environmental effects associated with burning of solid fuels using inefficient cookstoves. The review deepens the understanding on various clean energy interventions and policy formulation in several countries within the Southern Africa Development Communities (SADC) region. Studies indicated the development of stove alone will not be enough in enhancing or reducing air pollution, but emphasis shall be put on stove to fuel combination. Findings also suggest a lack of clear or practical policy intervention to restore household indoor air quality, while single policy intervention proven inadequate in many studies. In sub-Saharan region, policy intervention focuses on energy switch thus from traditional solid fuels to modern energy resources namely electricity and liquid petroleum gas (LPG). This approach is not feasible given the difficulties in electricity generation and supply system, housing infrastructure and cost implication. In conclusion, policies which support energy stacking present a viable solution to improved indoor air quality.

***Index Terms*— public health, small scale fixed bed and combustion technologies**

1 INTRODUCTION

Continued reliance on solid fuels such as coal, wood, cow dung, agriculture waste, charcoal and pellets is a marginalised developmental challenge in developing countries. Over 3 billion people have no access to clean or Morden energy, increasing reliant on high polluting energy sources [1]. Most of these exposures are experienced in sub-Saharan region of the developing world [2]. Problems associated with solid fuel combustion includes the release of harmful products resembling incomplete combustion process, leading to the release of carbonaceous and particulates emissions [3]. It is suggested that indoor air contains particulate and gaseous emissions which, are 20 times higher than World Health Organisation standards [1].

Women and children suffer the consequence of household air pollution [2].

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In recent literature it has been found that, exposure to poor indoor air quality is responsible for pre-mature deaths of 7 million people with 4.3 million deaths associated with poor indoor air quality and 3.7 million deaths due to ambient air pollution [4]. Adding to the cases of mortality, several cases of respiratory infections and morbidity are also linked to exposure to higher emissions from cookstoves [1].

Health related effects associated with poor indoor air quality are higher than malaria and tuberculosis combined, with anticipated more than 4000 lives lost per day by 2030, due to combustion by-products [2].

In this, light reports suggest that 17% of the global population do not have access to electricity, with 95% of the population with no access are found in Sub-Saharan Africa and developing Asia. Just 50% of the developing Asia relies on biomass and coal, while in the Sub-Saharan countries more than 80% of the population are using the coal and wood energy resource for cooking, water boiling and space heating [5]. In the developed nations of the world access to electricity from coal, wood and other reformed renewable energy sources is a living reality, having no population relying on dirty fuels for domestic activities [5].

This review paper aims at sharing light on various energy use scenarios in developing countries. The paper ends by looking at various policy interventions in three sub-Saharan countries (South Africa, Zimbabwe and Zambia).

2 ENERGY USE IN SADC REGION

In many SADC countries, access to electricity remains a developmental challenge, with fewer countries above 66% electrification as indicated in Table 1. Mauritius successfully reached 100% electrification, followed by South Africa at 85% and Botswana at 66%, while Malawi experienced the least electrification rate. However, electrification alone will not be adequate in addressing all household air pollution. In related research, it was found that over 75% of rural South African households continue to rely on coal and biomass fires despite electrification [6]. Therefore, the theory of energy staking relative to energy switch remains at the helm of household's energy interventions [7].

Table 1: SADC electrification rates in percentages of the country population?

Region	Population without electricity millions	National electrification rate %	Urban electrification rate %	Rural electrification rate %
SADAC	**634**	**32%**	**59%**	**17%**
Angola	15	30%	46%	18%
Botswana	1	66%	75%	54%
Kenya	35	20%	60%	7%
Lesotho	2	17%	43%	8%
Malawi	15	9%	32%	4%
Mauritius	0	100%	100%	100%
Mozambique	16	39%	66%	27%
Namibia	2	32%	50%	17%
South Africa	8	85%	90%	77%
Swaziland	1	27%	40%	24%
Zambia	11	26%	45%	14%
Zimbabwe	9	40%	80%	21%

Source: IEA, 2014

In reducing the consequences associated with household solid fuel burning, the focus shall be on replacing traditional energy combustion stoves [39]. The need to replace low energy efficient appliances with optimised cookstoves remains a valuable option [42]. The focus of energy combustion replacement was limited to replacing traditional cookstoves with improved cookstoves, but the penetration of energy replacement devices is lower in many developing countries, African in no exception [40]. Over the past 30 years, introduction of improved cookstoves has been practiced to reduce the health-associated effects of household air pollution [41].

However, many of improved cookstoves projects were not successful because some stoves lacked technical features during design thus leading to poor performance [8]. Most of the energy intervention (Improved stoves rollout) were derived from laboratory experiments, which often-overlooked cultural practices, stove tending and stove uses, leading to poor performance compared to field traditional stoves [9].

However, studies conducted by [10] indicated that, it would be imperative to design a better stove without the suitable fuel. In this regard, emphasis shall be given to both stoves to fuel combination rather than focusing on single attribute. Another study carried out by [11] on a systematic investigation on the effect of coal quality on emissions. In this study, it was found that, coal with a higher grade (A-Grade), produced higher emissions than a lower grade coal (D- Grade).

China is estimated to have a successful clean stove replacement program; with more than 40% of the population in need uses improved cookstoves [38]. While from the total of 3 billion global energy crisis associated population, only 828 million have access to clean cookstoves, with 116 million in china and Sub-Saharan Africa having the lowest number of population with improved cookstoves at 7 million [39].

Similar patterns of poor clean energy crisis in the Sub-Saharan regions are common. However, cultural practices and traditional technologies vary, leading to a range of combustion methods and devices. In the Sub-Saharan Africa, combustion of solid fuels is mainly done using traditional stoves, with population fewer than 7 million using improved cookstoves [40]. Traditional cookstoves are described as low efficient stoves which lead to poor combustion efficiency, low heat generation, transfer and poor fuel saving, as well as poor smoke extraction from enclosed kitchen spaces [13].

The Southern African Development Community, which is within the Sub-Saharan countries present vast opportunities in reviewing common knowledge and practices prevailing in the developing countries.

Combustion technologies of solid fuels however, in developing countries are influenced by the location and fuel availability. In South Africa, especially the central plateau of the Highveld, combustion technologies include burning coal using self-fabricated brazier colloquially termed *imbaula* (Braziers), while in the low veld rural areas the use of three stone fire stove is prevalent, with fewer commercial wood stoves being used [7], [14]. These stoves are designed using metal paint recyclable drums with no optimisation parameters, leading to poor combustion conditions as in Figure 1[15], [16].

Figure 3: Image of an *Imbaula* (Brazier)

In Zambia reliance on charcoal combusted using self-fabricated stoves is prevalent as in Figure 2. This device is made of recyclable metal with a fuel support grate and a tri-pot. The stove differs from one designer to the other, dictated by customer demands or requirements [16].

Figure 3: Image of the Zambian charcoal stove

In Zimbabwe, consumption of raw biomass is a major fuel source. Raw biomass is burnt in locally designed stove termed Tsotso. The stove is designed using recyclable metal, with ceramic lining as shown in Figure 3 [17]. The

ceramic lining is for increasing the thermal efficiency and heat retention.

Figure 3: Image of the Tsotso stove

Similarly, in three countries solid fuel combustion remain a major fuel source. However, the inception or adoption of ICS is minimum. Combustion devices often used to lit fires are self-fabricated. In addition to the sprawl of energy inequalities and harmful exposure, in some countries energy switch is viewed as a viable option. This approach provide a platform for energy provision and maintenance abundant [37].

Energy switch often favours people at higher economic brackets and often exclude low income or non-high income earners [12]. The emphasis on energy switch, which entails moving away from traditional fuels (coal, wood, husk and cow dung) to modern energy (electricity and LPG).

The proposed energy switch intervention have potential to restore indoor air quality as a long-term strategy, but in the interim, it shall be acknowledged that reliance on solid fuel will remain a commodity for foreseeable future.

3 Household air pollution (HAP) reduction mechanisms

In this light, South Africa as the largest populated country in the SADC region with over 50 million people, Zimbabwe and Zambia provide an excellent representation to investigate potential hazards associated with solid fuel burning technologies, policy interventions and barriers [3]. The three chosen areas present a wide spread of electrification rate within countries as shown in Table 1, South Africa, representing countries with high electrification brackets, with Zimbabwe and Zambia representing the middle and lowest electrification rate.

Recent literature by various authors provides significant knowledge and suggestion in policy attributions, potential developmental approaches in enhancing household air pollution problems in the Southern region. The following studies explicitly confer on several hindrances in achieving sustainable development goals through policy interventions. Such studies includes:

- Study on optimising the *imbaula* by [15], where the study highlighted preferred biomass combustion devices in South African peri-urban region and performance features, which can reduce exposure to noxious gases and particulates.

- Study on Optimisation of ventilation and ignition method for reducing emissions from coal-burning *imbaula* by [14]. In this study, several coal-burning devices were investigated for emissions and parameters needed for optimum performance.

- Performance evaluation of three charcoal stoves by [16], charcoal combustion devices used in Zambia, Madagascar and Mozambique, were evaluated for performance.

- Energy use scenarios in an informal urban settlement in Johannesburg, South Africa by [7]. In this study various energy resources applicable for low-income areas are highlighted, indication of the need for energy staking is shown.

- The potential and prospects of improved cookstoves (ICS) in Zimbabwe by [37], in this paper various approaches to energy expansion are highlighted, with policy barriers and lower dissemination of improved cookstoves inception.

- Global Alliance for Clean Cookstoves South Africa Market Assessment Sector Mapping [18].

- Energy Policy in Zambia by Muzeya [44], a draft renewable policy in Zambia highlights an urgent need in providing clean energy resources for all in the republic.

4 Residential energy use in Southern Africa context

This section presents the findings of the study. The findings are divided in two parts: solid fuel use in low-income settlements and clean energy policies.

4.1 Solid fuel use in low-income settlements of South Africa

In South Africa, half of population to date depend on open fires using coal and wood for cooking, water boiling and space heating. Only a small fraction of this population burn good quality fuels with the correct moisture content, leading to poor efficiencies [18]. Adding to the problem, solid fuel combustion devices are not standardised; it is dominated by the use of self-fabricated devices, while fewer burning appliances are available in formal commercial outlets.

Majority of coal and biomass fuel combustion devices found especially in peri-urban settlements are obtained from the black market (informal trading) acquisition process [14, 15]. Biomass reliance is estimated to supply 20% of the total energy resources for domestic cooking and space heating in low veld and rural areas. The challenge of this higher biomass combustion is linked with several environmental degradations including deforestation and potential poor environmental hygiene. Wood consumption in many setting involves the use of unprocessed wood with higher volatiles and moisture content.

The use of high moisture content and volatiles organic compounds presents favourable conditions for higher emissions and poor combustion efficiency, especially when combustion is done in poorly optimised and non-standardised devices [14], [19]. Poor household air quality resulting from poor combustion of solid fuel was responsible for 1 400 pre-mature deaths between the year 2009-2010 [34]. While on the other hand, the National

treasury had to spend R1.2 billion per year on treatment of lower and upper respiratory infections [20].

4.2 Clean energy policies in South Africa

In South Africa there was a shift in paradigm during the early 1990s where electrification was introduced in urban areas, with emphasis on energy switch. After the 1994 election, the newly elected government formulated mass electrification policy, which focused on both rural and urban electrification. To date more than 87% of households are connected to the electricity grid, however, dependence on solid fuel continue to cause household air pollution and consequence of public health [35].

In the energy policy for sustainable development, it is recommended that in order to address the burden of air pollution, there must be several strong integration of energy supply resources. In addition, it was shown that, energy switch is dependent on several factors, poverty being a major obstacle or barrier [6]. This finding further indicated that, access to electricity does not guarantee affordability.

Therefore, a single energy policy intervention will be inadequate in addressing household air pollution problems [18]. Although electricity has received social acceptance and proven to be the energy of choice, it is also important to integrate other energy options to supplement the supply. Studies conducted by [7], found that, in all household the use of more than one fuel was prevalent. Moreover, policy formulation should address the need for energy staking rather than focusing on energy switch as a probable short-term interim. There is slow dissemination of improved cookstoves (ICS) due to initial device capital thus from coal/wood to LPG and other energy sources perceived cleaner as shown in Figure 4 [20]. Reluctance to switch from solid fuel to clean energy resources is influenced by initial capital cost behind the technology.

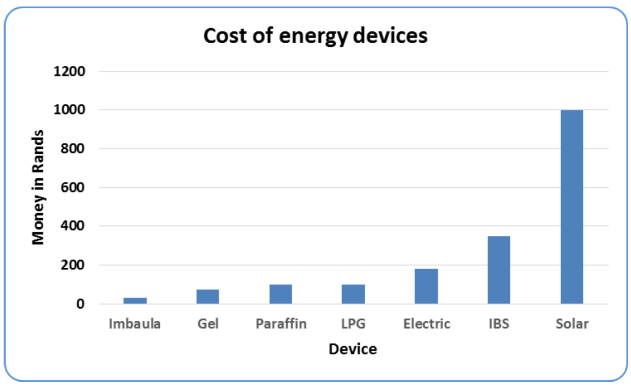

Figure 4: Cost of energy appliances in South Africa
Source: GACC, 2014

South African energy expansion plan targets 92% of household connection to the grid by the year 2025, with a massive growth in renewable energy investment and supplementing coal-powered generation [35]. This intervention will be a greater achievement, however, if there will be no other policies, that promote lower electricity tariff, continued reliance on cheap or free available solid fuels will persist [36].

4.3 Solid fuel use in Zimbabwe

After the economic meltdown in Zimbabwe in the mid-1990s, electricity generation utility became under economic strain, which complicated the ability to supply clean energy resources [21]. Failure to sustain the grid power generation called for additional alternatives which, saw population relying on wood for major domestic household activities. Similar to South African rural and urban situation where wood is also a preferred energy alternative [15], [22], [23]. The difference in this regard, is that, in Zimbabwe coal is not an abundant resource, with a lesser percentage connected to the electricity grid [2]. The Zimbabwean's approach to clean energy crisis is not different to the rest of the world, which seeks to promote low cost energy alternatives and open to private investment in large and small scale power generation [24].

Most of the energy interventions are entailed in policy draft documentation; there is paucity of information which, lack mandatory [24]. Although the use of solid fuel remains one of the key factors in achieving sustainable development goals, there is a continued ignorance from government side in supporting health promotion programs [25]. The dissemination of improved cookstoves is a key program in alleviating energy poverty and reduces exposure to noxious gases and particulates [25]. Improved cookstoves are used in all part of the world due to their proven ability in reducing exposures and improving general environmental health of the public including indoor environments [26]. In Zimbabwe inception of improved cookstoves is lower as in the case of other developing countries [27]. The main identified barriers are at institutional level, economic transits, local infrastructure, price distortion, policy and political bureaucracy.

In summary ICS dissemination programs continue to be less prioritized from the ministry of the Department of Energy in Zimbabwe. This led to failure of such programs to make a positive contribution to improved indoor environment [28].During economic meltdown during the 1990s, Zimbabwean government was forced to develop Economic Structural Adjustment Program which, indicate lack of financial resources to assist in ICS programs [36]. Adding to the problem was the political instabilities in the country, increasing probability of price distortion of stoves by sellers. Continued price distortion was influenced by non-policy adoption regulating ICS projects.

4.4 Clean Energy policies in Zimbabwe

In the draft energy policy, efforts were directed to promote the use of low cost and clean energy alternatives, with wood the primary targeted fuel source and increase public participation. However, there is little involvement from the national department of energy at local levels [29]. Lack of governmental representation contributes to poor facilitation of energy alternatives. The decision to reform the economic policy in the 1990 which, was termed until

1995 also contributed to lack of funding opportunities for small-scale combustion alternatives [7].

Now there is a growing concern for dissemination of improved cookstoves in Zimbabwe; notably the plan to provide renewable energy technologies. However, improved cookstoves (ICS) program continues to be ignored by the political sphere. It is anticipated that, if the energy alternative plan is adopted there will be a greater potential to increase accessibility, affordability of renewable energy technologies, improving indoor air quality while at the same time protecting the environment.

Embedded to the problem is the price distortion from government or agencies, where improved cookstoves are twice to three times expensive than traditional stoves. Stove dissemination programs should encounter local merchandises and provide competitive edge, should the program desire adoption.

Improved cookstoves can have a better saving in a long run with better returns; however, the initial capital investment and fuel availability might hinder adoption. Another barrier in improved cookstoves adoption is the durability of construction materials often perforated, and parts such as fire grates not easily available or replaceable. Some improved cookstoves perform better in the laboratory and after field rollout, report lower efficiencies. This is factored by lack of standard protocol for testing of field cookstoves, which mimic field stove use, and tending methods.

Small scale improved cookstoves project receive little financial support from governmental agencies. This results in poor acceleration of project relating to technical aspect consideration, fuel quality assessment, distribution of information and project monitoring. The funding agencies and Zimbabwean banks make it difficult for small-scale improved stove projects to access loans. This affects the dissemination of various renewable energy technologies. Although, government subsidy on stove projects has several limitations, there is a need for governmental financial support structure to accelerate the inception of ICS [41].

Technical conceptual designs compromised the adoption of several improved cookstoves in Zimbabwe. In the case of the Tsotso stove dissemination program, the stove was rated good by user at a short term due to fast cooking, portability and fuel saving. However, later the stove was criticised for damaging cooking vessels, this analogy should have been noted during stove testing looking at the firepower [37].

Another case was in *Yugen* mud stove program, where the stove was not suitable for the local infrastructure due to its larger size, which did not fit inside the kitchen. The stoves were erected outside the kitchen with the wire mash required to reinforce the mud. The bottom ash hole at later stage became a habitat for snakes and rodents, with community on later stage resorting back to use their traditional cookstoves [24].

All improved cookstoves programs collapsed in Zimbabwe soon after the donor funding was terminated and there was little emphasis on technical design aspect, poor project implementation and public participation.

4.5 Solid fuel use in Zambia

Zambia experiences massive poor electrification rate in both rural and urban settings. Just less than 3% of rural households with less than 18% of urban households are electrified. Lowers electrification rate force people to rely on alternative basic energy. Zambia enjoys government heritage forests resource that, supply more than 85% of the population with fuel to cook and warm their houses. Harvesting and processing of raw biomass for charcoal production is a major energy practice in Zambia. These fuels are burned using self-fabricated metal stoves with no emissions reduction and fuel economy benefit. Compared to South Africa, access to clean energy in Zambia is quite poor, with a greater need to introduce biomass energy regulatory policies to protect forests. There is a slow policy progression in Zambia to facilitate improve cookstoves dissemination programs at the ministry level of Department of Energy [37].

Without policy intervention on biomass energy it will be difficult to incorporate technical designs, funding method, public participation and stove benefits offset monitoring as in the case of Zimbabwe. Despite a greater need for dissemination of improved cookstoves projects similarly to Zimbabwean situation, there is a low inception of cookstoves at community level. In Zambia, reliance on biomass renewable energy is not only viable in rural or poor communities as in South African situation; the problem is quite severe due to inconsistency even in richer areas.

4.6 Clean Energy policies in Zambia

Zambian short-term clean energy expansion policy lacks directive, whereby emphasis is given to long-term power generation master plan of 66% electrification by 2030 [44]. This calls for an urgent need to develop sustainable short-term energy plan for residential areas especially in the rural areas under the poverty line.

4 RECOMMENDATION

Similarly, within the SADC region energy inequalities persist, with weaker policy formulation and ICS adoption. It can therefore, recommended for a universal policy formulation which, will focus on energy resource expansion, sharing and technical development of testing methodology of ICS. The policy must address the local need in accessing clean energy supply, fuel access, low cost stoves and public engagement and participation.

In some areas, policy formulation process might be slower than expected; hence, there is a need to formulate universal household energy policy, which will facilitate adherence to indoor air quality levels in line with the World Health Organization guidelines. There must be a financial structure in the SADC region that will enhance easy access to funding of testing laboratory, ICS design programs, public consultation process, project implementation and monitoring.

Notably, in literature successes of ICS programs in China and Kenya made major impacts in enhancing air quality and environmental benefits, followed was extensive researches done to evaluate the effectiveness of

such stoves [30], [31], [32]. We recommend extensive research to be done in the SADC region investigating the cost barriers and contribution of ICS, public participation, renewable energy growth potential and social marketing initiatives.

The SADC region to formulate a specialized policy review committee, which will assist in evaluating practical application of energy plan, technical expertise in stove design, fuel analysis and the cultural relevance of adopted or formulated test methods. The SADC, ICS policy formulation must emphasize on improving fuel saving thus minimizing deforestation, low cost technology, accessible design features including material, good quality fuel, funding of ICS programs, effective implementation, and monitoring, improved public participation and customer feedback.

Since not all clean energy interventions are unaffordable, there is a need to regulate biomass forest destruction through policy. It is evident in literature that strict governmental regulations are required to foster compliance and facilitate the success of clean energy programs. However, there is a compelling need to evaluate the contribution of ICS in improving general environmental health of the public.

5 CONCLUSION

This review paper indicated various energy inequalities within the SADC region. The paper demonstrated continued reliance on solid fuel burnt using inefficient stoves as a major cause of household air pollution and public health consequence.

Although clean energy programs such as urban and rural electrification and LPG rollout sound to be good models, this articles highlighted on several barriers which, suggest that LPG and electrification as a short-term strategy to alleviate environmental consequences arising from inefficient cookstoves as not realistic in many countries within the SADC region.

Therefore, with proper project design, implementation and monitoring ICS programs provide a realistic tool to minimize environmental risks resulting from open fires from domestic cookstoves for decade to come. ICS policies must be formulated and support programs in several ways including regulatory framework for biomass usage, financial support, technical support and program reviews.

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