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Review

# Fuel switching and energy stacking in low-income households in South Africa: A review with recommendations for household air pollution exposure research

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ABSTRACT

Households stack and switch the fuels they use to meet their energy needs for cooking, heating and lighting. The type of fuel used and how fuels are stacked and switched affects household air pollution concentrations and consequently impacts human health. Fuel use patterns are often incorporated into household air pollution studies as an exposure proxy, but this is not always done in a comprehensive manner, especially as the fuel stacking and switching phenomena are excluded from the research methodology. Many low-income households in South Africa do and are likely to continue to stack and switch the fuels they use, including a range of polluting energy sources such as coal or wood, substantially contributing to the country's disease burden. This review paper sought to identify how studies have assessed fuel stacking and switching in the context of household air pollution studies to help guide researchers to develop improved surveys and questionnaires which incorporate household fuel stacking and switching practices in a more detailed manner for exposure studies. While quantitative data remains the gold standard, obtaining detailed information on fuel use practices can significantly improve our understanding of associated air pollution exposure. We demonstrate that more comprehensive and localized studies are necessary when we seek to fully understand fuel stacking and switching practices for household air pollution exposure studies in epidemiological research. This is also important for effective policy development and implementation.

## 1. Introduction

The energy sources used by households to cook, to heat and/or to light their homes influence the health and quality of life of household members [1]. In low- and middle-income countries (LMICs), households interchangeably use a wide spectrum of practices, devices and fuels to meet their energy needs [2–5]. As fuel use practices frequently change, questions about predominant fuel types for heating, cooking or lighting activities, are not straightforward to answer as many households stack or switch fuel combinations, despite having access to electricity or other modern energy sources [5,6].

Explanations for this multi-energy source use approach are associated with socio-cultural and pragmatic factors, economic constraints, access to energy sources and quality of service, among others [5]. Energy service (like cooking, heating or lighting) also represents a deciding factor in energy source choice. This is because electricity may be used for lighting in an electrified house, for instance, but a coal stove may also be used for cooking or space and water heating in the same house. Seasonal changes and geographic location also influence fuel use patterns [5,7]. Fuel availability or fuel preference may change depending on the season, for example, some biomass types used for burning may only be available during summer or autumn following the rainy season in the austral summer. Inland households may require solid fuels in winter to heat their homes at night [5,7]. Additionally, households located in more rural areas may have easier access to wood than those living in urban centres [5,7]. Overall, stacking with more traditional

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fuels has been linked to contextual drivers including the social environment of cultures and norms or the physical environment within which people interact and live [8]. These factors include affordability, cultural compatibility, end uses of traditional stoves, equipment compatibility, stove functionality, household dynamics, knowledge and training, safety issues, fuel supply issues, technical characteristics and time aspects [8].

Several theories aim to explain the complexities of using multiple fuels, with the most common being the concept of the 'energy ladder' and the practice of 'energy or fuel stacking' [9]. According to the energy ladder hypothesis, households move in a linear and upward manner and switch from traditional and 'dirty' fuel types, like wood and dung, to more modern and cleaner technologies such as liquid petroleum gas (LPG) and electricity. This occurs as a household's income increases and/or relative fuel costs decrease [10]. Contrary to this, the energy stacking theory states that households may simultaneously rely on both traditional and more modern fuel types and appliances based on various factors, as listed above [10].

The fuel stacking framework is widely accepted for understanding domestic fuel use complexities [11]. Most recently, a household energy transition index has been formulated which considers the energy ladder and the fuel stacking theories. It emphasises that both of these theories do not adequately describe the intricacies of household fuel choice behaviour and households' move towards cleaner fuels [12]. The index proposes that the consumption of cleaner fuels in the energy transition does not only depend on economic factors, but also on various behavioural factors, e.g., female bargaining power and educational level which both increase the likelihood of using cleaner fuels [12].

Although many households can only afford to use polluting fuels, this apparent cost-saving is accompanied by hidden, long-term societal expenses with women often bearing a disproportionate burden [13]. This includes time poverty based on the time that is spent on the collection of such fuels or increased cooking times [14]. The use of these fuels can also lead to aesthetic damages such as when vegetation is removed to harvest wood for energy, impacting both homes and their surroundings. There are wide-ranging environmental consequences associated with the use of polluting fuels including contributions to climate change. Household use of polluting fuels in a dwelling also contributes to negative physical health impacts as well as mental health impacts and depression [15].

Household air pollution (HAP) resulting from reliance on traditional and dirty fuels such as wood, crop residues, coal, or dung is associated with increased risk of respiratory infections (e.g., asthma, acute respiratory infections, chronic obstructive pulmonary disorder, lung cancer), and also with cerebrovascular disease, ischemic heart disease, low birthweight, stillbirth as well as under-5 respiratory and cardiovascular mortality, diabetes and lower sperm count [16–21]. Even though the world is making progress towards universal access to clean household energy, globally 47 % of households use fuels which contribute to HAP [22]. In 2019, 2.31 million global premature deaths were attributed to HAP (4 % of all deaths in that year) and HAP-related deaths are estimated to be two times higher in countries with low socio-economic status than in countries with higher socio-economic status [23,24]. Future projections suggest that by 2030, 31 % of the global population will still mainly use polluting fuels like biomass, coal, charcoal and kerosene, and that in the next two years, one billion people in sub-Saharan Africa will rely on such fuels continuing to expose themselves to high levels of HAP [25].

Research studies aim to understand HAP exposure levels in indoor settings to assess associated impacts on human health. The most efficient and cost-effective methods involve questionnaires or surveys using indicators like fuel use patterns to estimate HAP exposure [26]. Alternatively, direct pollutant measurements, though more costly and time-consuming, can be used. Most frequently, research studies use the first method due to financial or other constraints. Such surveys then focus on a household's primary fuel choice as an exposure proxy. National data on energy use patterns, for example, are collected by means of national census surveys [27]. In such surveys questions are asked about primary fuel type choices for activities like cooking, heating and lighting. It is rarely the case though that questionnaires include questions about multiple fuel use patterns, including fuel stacking and switching habits. These omissions may lead to incorrect assumptions about HAP exposure as this approach does not consider the influence of a secondary (or even tertiary) fuel used by household [16].

There is a need for more nuanced and context-specific surveys to carefully assess household energy determinants and behaviours considering fuel stacking and switching habits to enable the development of more realistic personal HAP exposure proxies for epidemiological studies [16]. This is crucial when trying to estimate the burden of disease placed upon households by their fuel use patterns, especially given the nonlinearity of the HAP exposure-response function which means that pollution levels have to fall to low levels to deliver a large health benefit [28]. Surveys designed specifically to determine the health impacts of fuel use patterns and that consider fuel stacking at a household level are uncommon. Moreover, studies using primary energy data to understand the associations between fuel use and health may over- or underestimate the true relationship between fuel use, HAP and human health impacts [22].

Household fuel use patterns are highly heterogeneous in South Africa and typically vary depending on geographical location, cultural preferences, income, availability, among other factors [29]. For instance, in cases where electricity is either inaccessible or unaffordable, low-income rural households living in areas where wood is readily available (e.g., parts of Limpopo Province) usually use wood as a primary fuel whereas more urban households use kerosene [27]. Contrary to this, low-income households located on the South African Highveld in Mpumalanga Province near coal mines often use coal for cooking and heating [30]. In 2021, a national household census stated that, across South Africa, 89 % of households were connected to the national electricity grid [27]. Despite this, not all of the electrified households made use of electricity for cooking. This has been linked to the provision of a free basic electricity (FBE) subsidy, where indigent households receive between 50kWh and 60kWh of free electricity per month to meet basic energy needs (e.g., lighting or charging phones) [31]. Once this subsidy runs out, even electrified households return to using other fuels [31]. In 2021, the main fuels used by households for cooking purposes were reported to be electricity (77.7 %), wood (7.7 %), gas (4.8 %), kerosene (3.5 %) and coal (0.4 %) (along with other unidentified energy sources (5.9 %) [27].

South African air quality studies suggest that people living in low-income communities experience the highest ambient particulate matter (PM) concentrations in the country, even when compared to industrial areas [32]. Household PM exposure in such areas is typically higher than the already high ambient air pollution exposure [33]. Fuel switching and energy stacking represent a persistent characteristic of the fuel use patterns of both electrified and non-electrified households in South Africa [34]. Additionally, the increased occurrence of rotational power outages due to electricity supply shortages has meant households have moved away from electricity to other fuels such as LPG, kerosene and solid fuels [35]. As South Africa's electricity crisis is predicted to worsen in the immediate future, the impacts this may have on household fuel choices and consequently on HAP levels and human health must be considered.

South African household fuel use patterns are complex and offer insights which can inform both local and global studies, but also energy policies and interventions. South Africa's diverse cultures, languages and traditions translate into a wide range of cooking practices, household compositions, behaviours and fuel stacking and switching habits [36,37]. Additionally, being one of the most unequal countries in the world, the economic disparities between poorer and wealthier households and also between rural and urban areas influence fuel choice [36]. This is not only because poorer communities often do not have the

**Table 1**
Search terms and boolean operators used to search databases to identify studies on fuel use (with an emphasis on fuel stacking and switching) and household air pollution in low-income communities in South Africa.

<table>
<tr><th></th><th>Relating to fuel use patterns</th><th>“AND”</th><th>Relating to household air pollution</th><th>“AND”</th><th>Relating to low-income communities</th><th>“AND”</th><th>Relating to South Africa</th></tr>
<tr><td>Main literature search</td><td rowspan="2">“Fuel use” OR “Fuel switching” OR “Fuel stacking” OR “Energy stacking” OR “Energy switching” OR “Energy ladder” OR “Fuel use patterns” OR “Energy poverty” OR “Energy profile” OR “Household energy”</td><td></td><td>“Indoor air quality” OR “Household air pollution”</td><td></td><td>“Low-income communities” OR “low-income households”</td><td></td><td>“South Africa”</td></tr>
<tr><td>Supplementary literature search</td><td></td><td>None</td><td></td><td>“Low-income communities” OR “low-income households”</td><td></td><td>“South Africa”</td></tr>
</table>

money to afford cleaner fuels, but also because more remote communities have not yet been electrified or have highly unstable electricity connections leaving no choice but to use dirty fuels that are often free to access [38,39]. Finally, South Africa's wide-ranging climate, including a winter-rainfall Mediterranean climate in the south-west, a hot desert climate in the western regions and a warmer subtropical climate in the north-east, requires different energy needs [40,41].

Against this background, the aim of this review was to understand how fuel stacking and switching information is gathered from households primarily for use in HAP exposure and human health studies for epidemiological research. The objectives of this review study were: 1) to identify what questions have been asked and what information has been gathered in previous studies to understand fuel stacking and switching in low-income households in South Africa and to see how these relate to HAP exposure and 2) to present a set of recommendations and guidance for future work in relation to household stacking and switching practices, which researchers can use to meaningfully support HAP exposure research. To facilitate a robust exploration of these two objectives, this study also synthesizes factors influencing fuel stacking and switching behaviour as outlined by the identified studies. This synthesis serves to contextualize and enrich the recommendations. Though generalized policy recommendations based on this review may not sufficiently reflect the disaggregated regional context, especially at a household level, we believe this would be relevant in the context of low-income households in South Africa, and other LMICs. Finally, this review was carried out as part of a larger project that investigated human health risks related to HAP exposure in low-income communities in South Africa, hence the application of the HAP lens here.

## 2. Methods

### *2.1. Literature search and screening strategy*

Existing literature on popular scientific databases was systematically reviewed by using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [42] but with slight differences in methods to accommodate all available evidence. Electronic databases, i.e., PubMed, Scopus and ScienceDirect, were searched for peer-reviewed studies written in English and published between 2011 and 12 October 2023 with a focus on titles, abstracts and keywords. The key terms were combined with the boolean operators “AND / OR” (Table 1) and the search strategies were tailored to each database (e.g., Medical Subject Headings (MeSH) terms were used in PubMed). The main literature search identified studies that considered energy use patterns in the context of low-income communities in South Africa and made mention of air pollution exposure (Table 1). A supplementary literature search was conducted using the same terms as the main review but omitting the air pollution exposure focus to ensure all relevant studies were included (Table 1). PubMed was not used for the supplementary search, since it did not have a health focus. The reference lists of included papers were searched to ensure that no relevant studies were omitted.

For both searches, the articles identified in the databases were imported into EndNote (version 20) for the removal of duplicate records [43]. All remaining records were imported into the online systematic review tool called Rayyan where four researchers (BW, CYW, AIH and GEM) removed any remaining duplicates and reviewed titles and abstracts against the specified inclusion criteria [44]. In total, the main review resulted in 28 unique records and the supplementary search in 25 unique records, adding up to a total of 53 articles (Fig. 1; Table 2 & Table A2).

Fuel use patterns were considered a proxy for HAP exposure. Thus, articles did not have to present physical air quality measurements to be included in the review. However, studies were required to have mentioned HAP in relation to fuel use patterns in order to be included given the focus of this research to identify questions for HAP exposure and health studies for epidemiological research. Studies did not have to address health outcomes or gather data related to health to be included. However, incorporating such studies would be a valuable expansion for subsequent reviews.

For the purpose of this study, we choose the terms ‘fuel stacking’ and ‘fuel switching’ to describe households' habits of using multiple fuels. This could mean using different fuels simultaneously for different purposes (an example of ‘fuel stacking’ could be a household using electricity for lighting, LPG for cooking and wood for heating). It could also mean using various fuels for the same purpose on an alternating basis (an example of ‘fuel switching’ could be switching from electricity for cooking at the beginning of the month to coal for cooking towards the end of the month).

### *2.2. Analysis of included articles*

To create a comprehensive overview of the included articles, we assessed these for commonalities and differences in terms of their study area, study designs and fuel use terminology, as well as other important characteristics (Table 2 and Table 3). The main fuels used for heating, cooking and lighting were identified for each study, as were fuel stacking and switching elements (Table 3). Data collection methods of the studies were captured, and overarching themes were contextualized for applicability in HAP exposure research. Factors influencing fuel use, fuel stacking and switching were identified and summarised for South Africa. Finally, the lessons learned that were presented in the articles were summarised, and suggestions for improved surveys and guidance

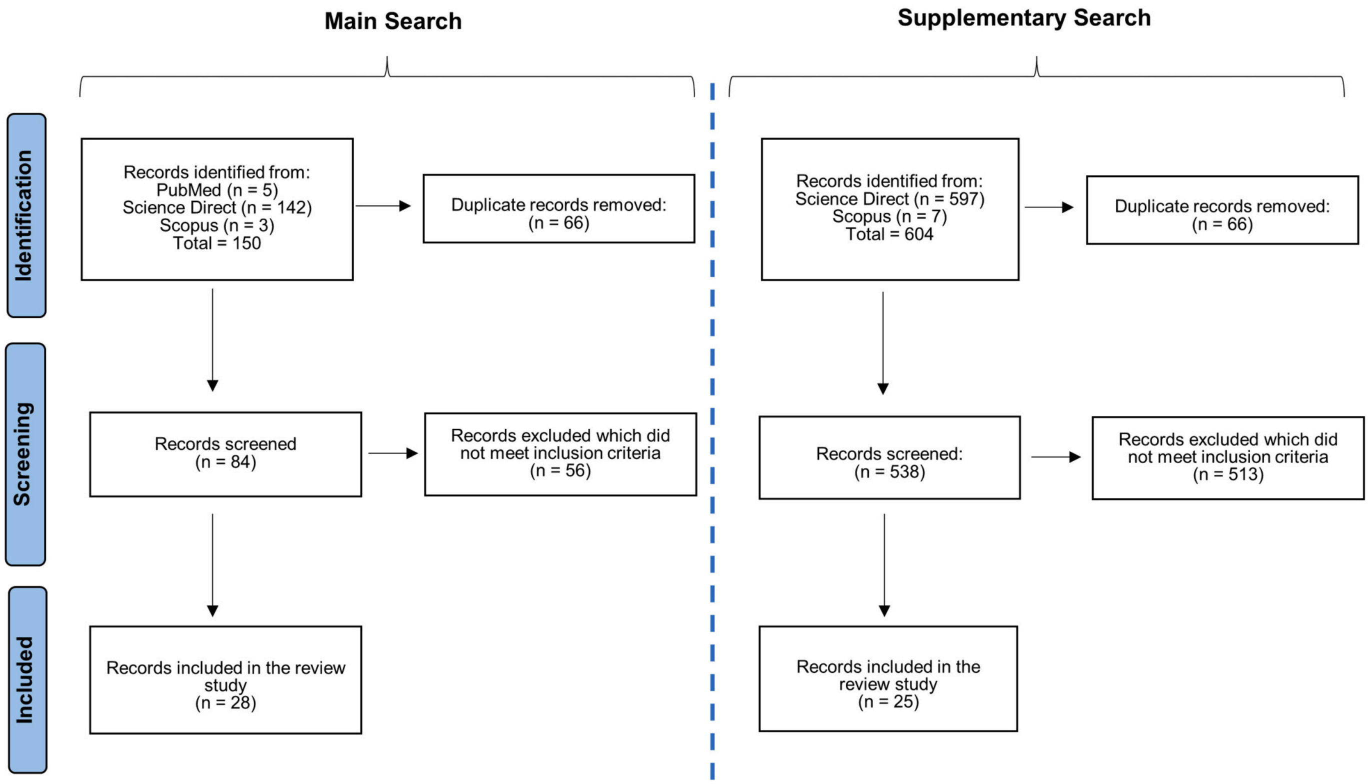


**Fig. 1.** Adapted PRISMA flow diagram showing the systematic review process from identification to extraction for the main and supplementary reviews.

for future studies were proposed. This was done to enhance research pertaining to fuel stacking and switching specifically in the context of HAP exposure in South African communities.

## 3. Results and discussion

### 3.1. Themes and methods of South African energy stacking and switching studies

All studies mentioned or observed the use of multiple fuels in low-income households in South African communities (Table A1 and A2). Most of the articles focused on understanding energy use behaviour, perceptions and preferences at a household level, with the aim of understanding the factors influencing fuel use consumption patterns, e.g., cultural, financial or socio-economic factors (Table 2).

Access to electricity and electricity consumption patterns were frequently researched, mostly in relation to the poverty line as well as energy poverty and how these concepts relate to electrification rates in South Africa [45,46,50–52,78,85,92–95]. Other articles either evaluated interventions or new technologies and their impact on fuel use patterns, investigated energy use patterns in general, considered transitions in relation to multiple fuel use theories or assessed emission risks associated with fuel use patterns [4,47,57,59,65,69,79,82–84,86–89,91]. Furthermore, studies focused on energy consumption and efficiency [74–76,81], safety related to fuel use [77,80] and gender-related factors [90,91].

While at least one study was conducted in each of the nine provinces of South Africa, most of the studies were conducted in the provinces in which the largest urban hubs are located (i.e., Western Cape, Gauteng, and KwaZulu-Natal Provinces). Almost a third of studies took place in provinces known for heavy reliance on solid fuels for domestic energy needs (i.e., Limpopo and Mpumalanga Province, where wood and coal, respectively, are used). The Free State and the Eastern Cape were the least represented provinces (Table 2 and Table 3). Almost half of the studies considered country-wide data (mainly based on existing national surveys) and looked at both urban and rural communities.

Just under 60 % of the studies were cross-sectional in design and their data collection methods were based on the administration of questionnaires that used self-reports from participants at a household level (Table 3). Five articles presented results of longitudinal studies [50,56,63,71,92], two were controlled trials [39,75], two were experimental [87,88] and the remaining studies were based on findings of literature reviews [49,52,54,59,60,66,72,82,86,94,98]. Other ways in which information was gathered from participants was through focus group discussions and diary entries, but many studies also used secondary data for their research which they sourced from previous census or panel studies.

The most common energy transition and fuel use pattern terminology used in the reviewed articles was, in order of frequency of occurrence and quoted verbatim, 'energy ladder', 'fuel switching', 'fuel stacking', 'energy stacking', 'energy mix' and 'multiple fuel use' (Table 3). 'Stove stacking' and 'technology stacking' were mentioned to illustrate the use of multiple devices to meet household cooking or energy needs.

More than 90 % of the studies assessed households' fuel use patterns in relation to cooking. Just over two-thirds of the studies considered the types of energy households used for lighting. About half of the studies aimed to gain insights into how households met their heating needs (including space and water heating). Appliances and cooling methods (like the use of fans or air conditioning) were also assessed.

Most homes were electrified, and electricity was the main fuel households used for cooking, heating and lighting when an electrified house could afford it [46,48,50,53,60–62,65,67,68,71,85,91] (Table 3). Wood, dung and other biomass fuels were the second most frequently used fuels for cooking [46,53,57,61,67,68], followed by LPG and kerosene [46,48,58,61,65,85]. Fuels used for heating were diverse across the studies, with wood as the primary non-electric fuel in the colder months [53,58]. Coal was used in households on the Mpumalanga Highveld [39]. Electricity, kerosene and LPG were the fuel types used after wood or coal in homes in which electricity was not affordable for heating

**Table 2**
Geographical location, main study design and study theme category of the studies included in the main and supplementary searches. For a more detailed summary of the studies, see Supplementary Tables A1 and A2.

| | Author and year of publication | Geographical location | Main study design | Study theme category |
|---|---|---|---|---|
| Main search: | | | | |
| 1 | Vermaak et al., 2014 [45] | South Africa as a whole | Cross-sectional | Electricity consumption patterns |
| 2 | Musango 2014 [46] | Gauteng Province, South Africa | Cross-sectional | Electricity consumption patterns |
| 3 | Kimemia and Annegarn 2016 [47] | Atteridgeville Township, City of Tshwane, Gauteng Province, South Africa | Cross-sectional | Interventions and fuel use patterns |
| 4 | Makonese et al., 2016 [48] | Vusimuzi, Madela Kufa Section 1 and Madela Kufa Section 2 (three informal settlements), Tembisa, Ekurhuleni Metropolitan Municipality, Johannesburg, Gauteng Province, South Africa | Cross-sectional | Understanding domestic fuel use mix |
| 5 | Brown et al., 2017 [49] | South Africa as a whole | Review | Interventions and fuel use patterns |
| 6 | Harris et al., 2017 [50] | Agincourt, Mpumalanga Province, South Africa and South Africa as a whole | Cross-sectional approach and longitudinal | Electricity consumption patterns |
| 7 | Mbewe 2018 [51] | South Africa as a whole and at a province level | Cross-sectional | Electricity consumption patterns |
| 8 | Tait 2017 [52] | Manenberg and Masilunge (two poor settlements that were surveyed in Cape Town, South Africa) | Review | Electricity consumption patterns |
| 9 | Uhunamure et al., 2017 [53] | Altein, Botsoleni, Makhovha and Thenzheni in the Thulamela municipality, Limpopo Province, South Africa | Cross-sectional | Driving forces behind fuel use patterns |
| 10 | Baptista 2018 [54] | Sub-Saharan Africa | Review | Energy use transitions |
| 11 | Bohlmann et al., 2018 [55] | Across the country of South Africa | Cross-sectional | Understanding domestic fuel use mix |
| 12 | Israel-Akinbo et al., 2018 [56] | Large national panel study (the whole of South Africa) | Longitudinal | Energy use transitions |
| 13 | Pailman et al., 2018 [57] | Gauteng, North-West and KwaZulu-Natal Provinces, South Africa | Cross-sectional | Interventions and fuel use patterns |
| 14 | Buthelezi et al., 2019 [58] | Umlazi Township in the City of eThekwini, KwaZulu-Natal Province, South Africa | Cross-sectional | Health risks associated with fuel use patterns |
| 15 | Hohne et al., 2019 [59] | South Africa as a whole | Review | Interventions and fuel use patterns |
| 16 | Kasangana and Masekameni 2019 [60] | Numerous studies in South African provinces, towns and different settings | Review | Driving forces behind fuel use patterns |
| 17 | Lusinga and de Groot 2019 [61] | Khayelitsha, Cape Town, South Africa | Cross-sectional | Driving forces behind fuel use patterns |
| 18 | Mulumba et al., 2019 [62] | KwaZamokuhle Town, Mpumalanga Province, South Africa | Cross-sectional | Understanding domestic fuel use mix |
| 19 | Shupler et al., 2020 [63] | Potchefstroom, North-West Province and Cape Town, Western Cape Province | Longitudinal | Energy use transitions |
| 20 | McCarron et al., 2020 [64] | Numerous countries, including South Africa | Cross-sectional | Driving forces behind fuel use patterns |
| 21 | Naidoo 2020 [65] | The community of Cato Manor, located in Durban, KwaZulu-Natal. Within Cato Manor, there were two targeted communities, namely Wiggins and uMkumbaan | Cross-sectional | Interventions and fuel use patterns |
| 22 | Gill-Wiehl et al., 2021 [66] | Numerous countries, including South Africa | Review | Driving forces behind fuel use patterns |
| 23 | Manyatsha et al., 2022 [67] | Ga-Molepo, Boshega village, Polokwane local municipality, Capricorn district South Africa | Cross-sectional | Driving forces behind fuel use patterns |
| 24 | Adeeyo et al., 2022 [68] | Lulekane, Majeje and Makushane villages, Phalaborwa, Ba-Phalaborwa Local Municipality, Mopani District, Limpopo Province, South Africa | Cross-sectional | Emission risks associated with fuel use patterns |
| 25 | Pauw et al., 2022 [39] | Highveld, Mpumalanga Province, South Africa | Review and cross-sectional, non-randomized controlled trial | Understanding domestic fuel use mix |
| 26 | Phogole et al., 2022 [69] | KwaZamokuhle, Highveld, Mpumalanga Province, South Africa | Cross-sectional | Interventions and fuel use patterns |
| 27 | Roomaney et al., 2022 [70] | South Africa as a whole | Cross-sectional | Health risks associated with fuel use |
| 28 | Gelo et al., 2023 [71] | South Africa as a whole | Longitudinal | Energy use transitions |
| Supplementary search: | | | | |
| 29 | Matinga et al., 2014 [72] | South Africa as a whole | Review | Electricity access and consumption |
| 30 | Ismail and Khembo 2015 [73] | South Africa as a whole | Cross-sectional | Energy use behaviour, perceptions and preferences |
| 31 | Nel et al., 2016 [74] | South Africa as a whole | Cross-sectional | Energy use behaviour, perceptions and preferences |

(*continued on next page*)

**Table 2** (*continued*)

| | Author and year of publication | Geographical location | Main study design | Study theme category |
|---|---|---|---|---|
| 32 | Thondhlana and Kua 2016 [75] | Grahamstown, Eastern Cape, South Africa | Non-randomized controlled trial | Intervention / technology study |
| 33 | Curry et al., 2017 [76] | Tshwane, South Africa | Cross-sectional | Intervention / technology study |
| 34 | Kimemia and Van Niekerk 2017 [77] | South Africa as a whole | Cross-sectional | Intervention / technology study |
| 35 | Runsten et al., 2018 [78] | South Africa, Cape Town | Cross-sectional | Electricity access and consumption |
| 36 | Ateba et al., 2018 [4] | Mafikeng, Potchefstroom, Pretoria, Johannesburg, Gauteng, South Africa | Cross-sectional | Electricity access and consumption |
| 37 | Kambule et al., 2019 [79] | Orlando East and Diepkloof in Soweto, Gauteng, South Africa | Cross-sectional | Energy use behaviour, perceptions and preferences |
| 38 | Kimemia et al., 2018 [80] | Johannesburg, South Africa | Cross-sectional | Intervention / technology study |
| 39 | Ye et al., 2018 [81] | South Africa as a whole | Cross-sectional | Electricity access and consumption |
| 40 | Adenle 2020 [82] | South Africa as a whole | Review | Intervention / technology study |
| 41 | Adesina et al., 2020 [83] | KwaZamokuhle in Mpumalanga, South Africa | Cross-sectional | Household fuel use and exposure |
| 42 | Rasimphi and Tinarwo 2020 [84] | Vhembe district in Limpopo, South Africa | Cross-sectional | Intervention / technology study |
| 43 | Strydom et al., 2020 [85] | Cape Town, Western Cape, South Africa | Cross-sectional | Energy use behaviour, perceptions and preferences |
| 44 | Dumont et al., 2021 [86] | Johannesburg, Gauteng, South Africa | Review | Energy use behaviour, perceptions and preferences |
| 45 | Makonese et al., 2020 [87] | Alexandra Township in Johannesburg, Gauteng South Africa | Experiment | Intervention / technology study |
| 46 | Sumbane-Prinsloo et al., 2021 [88] | Kwadela Township in Mpumalanga, South Africa | Experiment | Intervention / technology study |
| 47 | Haque et al., 2021 [89] | Joe Slovo in Cape Town, Western Cape, South Africa | Cross-sectional | Energy use behaviour, perceptions and preferences |
| 48 | Ngarava et al., 2022 [90] | South Africa as a whole | Cross-sectional | Electricity access and consumption |
| 49 | Ojong 2021 [91] | South Africa as a whole | Cross-sectional | Energy use behaviour, perceptions and preferences |
| 50 | Ye and Koch 2021 [92] | South Africa as a whole | Longitudinal (prospective cohorts and panel data) | Energy use behaviour, perceptions and preferences |
| 51 | Monyai et al., 2023 [93] | Gqeberha, Komani, Eastern Cape, South Africa | Cross-sectional | Electricity access and consumption |
| 52 | Said and Acheampong 2023 [94] | South Africa as a whole | Review | Electricity access and consumption |
| 53 | Ye and Koch 2023 [95] | South Africa as a whole | Cross-sectional | Electricity access and consumption |

**Table 3**
Characteristics of the studies on fuel stacking and switching in South African low-income communities in all 53 articles.

| Characteristic | | Number of studies ($N =$ 53) |
|---|---|---|
| Geographic location | South Africa as a whole | 22 |
| | Gauteng | 13 |
| | North-West | 6 |
| | KwaZulu-Natal | 6 |
| | Eastern Cape | 5 |
| | Mpumalanga | 7 |
| | Free State | 3 |
| | Limpopo | 7 |
| | Western Cape | 11 |
| Overarching theme | Fuel use and health | 1 |
| | Household energy transitions | 19 |
| | Household fuel use and exposure | 10 |
| | Household energy mix | 13 |
| | Electricity access and consumption | 21 |
| | Intervention / technology study | 14 |
| | Energy use behaviour, perceptions and preferences | 29 |
| Settlement types | Rural | 28 |
| | Rural and urban | 33 |
| | Peri-urban | 12 |
| | Urban | 34 |
| Data collection methods | Surveys | 19 |
| | Focus groups | 8 |
| | Secondary data (e.g., from census, originally cross-sectional and panel studies) | 14 |
| | Diaries | 1 |
| | Systematic review/ review study | 8 |
| | Survey of technologies | 6 |
| Study design | Longitudinal (prospective cohorts and panel data) | 5 |
| | Cross-sectional | 35 |
| | Scoping / Review | 12 |
| | Non-randomized controlled trial | 2 |
| | Experimental | 2 |
| Fuel use terminology in relation to transitions and fuel use patterns | Fuel stacking | 12 |
| | Energy stacking | 9 |
| | Fuel switching | 14 |
| | Energy switching | 1 |
| | Stove switching | 1 |
| | Energy ladder | 19 |
| | Stove stacking | 3 |
| | Technology stacking | 2 |
| | Energy mix | 8 |
| | Multiple fuel use | 8 |
| Energy services mentioned | Cooking | 49 |
| | Heating (without further elucidation) | 28 |
| | Space heating | 24 |
| | Water heating | 27 |
| | Lighting | 36 |
| | Cooling | 8 |
| | Appliances | 28 |
| | Home heating | 2 |
| Fuels used for cooking | Electricity | 25 |
| | Wood, dung, briquettes or other biomass fuels | 19 |
| | LPG | 17 |
| | Methanol/Ethanol | 2 |
| | Biogas | 3 |
| | Kerosene | 14 |
| | Coal | 11 |
| | Electric hob + battery | 1 |
| Fuels used for heating | Wood | 12 |
| | Coal | 11 |
| | LPG | 10 |
| | Kerosene | 10 |
| | Electricity | 18 |
| | Biomass | 7 |
| | Biogas | 2 |
| | Solar | 13 |
| | No heaters, but warm clothes | 4 |
| Fuels used for lighting | Electricity | 16 |
| | Candles | 10 |
| | Biogas | 1 |
| | Solar with batteries | 3 |
| | Kerosene | 11 |
| Fuel stacking and switching elements | Switch fuels between seasons | 9 |
| | Using various fuels to fuel traditional stoves | 3 |
| | Switch to dirty fuels when no electricity subsidy | 2 |
| | Kerosene/ wood over electricity when cooking for prolonged time | 2 |
| | Stove stacking | 4 |
| | Children and adults use different fuels | 1 |
| | Stack fuels when stove is insufficient for needs | 1 |
| | Stacking up the energy ladder as income increases | 1 |
| Health information | Health data collected (quantitative) | 1 |
| | Health data collected (qualitative) | 3 |
| | Health mentioned for context / background | 29 |
| | Health not mentioned at all | 17 |
| Air quality | Air quality data collected (quantitative) | 5 |
| | Air quality data collected (perception / qualitative) | 4 |
| | Air quality mentioned for context / background | 22 |
| | Air quality not mentioned at all | 21 |

Note: Totals do not need to add up to 53 as some articles included multiple options, and some studies excluded certain characteristics.

[47,48,53,58,61]. Even wearing warmer clothes or using a blanket was mentioned as a means to keep warm without spending money [47]. When electricity was not used for lighting, households relied on candles and kerosene [46,48,61,65,67].

Many electrified households used electricity for cooking, heating and lighting when provided with FBE, an electricity subsidy, but when this subsidy ran out, the households would resort to other, cheaper fuels for cooking and heating, like wood, coal or kerosene [39,46,47,67]. Similar findings applied to households receiving a pension grant [71]. Fuels like wood or coal were used more in winter months as these could be used simultaneously for cooking and for heating [39,47]. The duration of cooking time affected the selection of fuel type. Meals with a short cooking time were more frequently cooked using electricity or kerosene, whereas meals that took longer to cook were cooked using cheaper fuels like coal [48]. Electric stoves were more often used on weekends or in the summertime [57]. Children and adults living in the same household would use different fuels and appliances for different purposes. Children would be more likely, for example, to use electricity than their parents, who would use more traditional fuels for the same purposes [61]. Back up fuels were necessary when the electricity supply was unreliable or when the cooking appliance was insufficient for a large meal [49,60]. Peoples' attitudes, beliefs, perceptions and even feelings played a pivotal role in the acceptance of solar water heaters, for example, where a community resisted the roll-out of solar water heaters because they were considered ‘second-grade’ technologies and were an indication of social status [89]. Similarly, the use of biogas technology was found to trigger emotions of disgust and also of fear thereby limiting its use [86].

### 3.2. Data collection methods and information gathered

The main method of collecting data on fuel use was through asking questions using surveys, through focus groups or via requests for specific diary entries (Table 4). Questions regarding the expenditure patterns of the household were asked to find out how much money people spent on fuel on a daily or monthly basis for cooking and how much fuel they used. For example, studies enquired about the energy use quantities and costs and wanted to know the unit of sale for the fuel in use, the price per unit of the fuel, and the interval between purchases of the fuel [48]. Alternatively, questions were asked to gain a better understanding of how much a household was spending on fuel in relation to the household income [52]. One study weighed bags of coal sold to households by coal merchants, over and above asking households questions about fuel use patterns [39].

Only ten articles explicitly listed the questions they asked the respondents along with the possible response options [39,46,47,51,58,64,65,75,79,81]. These questions were either included in the articles or added as supplementary material. The remaining articles were assessed for what types of questions could have potentially been asked based on the information gathered as outlined in the results of the research (see Table A3 for a full list of questions). For example, if a study presented findings that the main energy source used for cooking was electricity or coal it could be deduced that the question the researchers had asked was "what main fuel type do you use for cooking?" and that the list of possible answers would include, electricity and coal. Most questionnaires included a question about electricity access and monthly expenditure on electricity.

Frequently, participants were asked to list the fuel they primarily used to cook, heat and light in their household. Respondents were asked to choose an answer from a list of provided responses (usually a list of fuel types ranging from modern (electricity, gas, solar energy and electricity from a generator), transitional (kerosene and coal) and traditional fuels (wood and dung)) [56]. In some studies, researchers went one step further to understand what secondary fuel respondents used in their households for the same energy use activities [47,48,65]. Some questions allowed for multiple responses and some allowed for open-ended responses without predetermined answers.

While the reviewed literature provided a good overview of fuel stacking and switching habits among low-income South African households, the limited number of longitudinal studies resulted in a lack of data with temporal variations. Consequently, many studies failed to capture the change in household fuel use patterns over time. Additionally, most of the studies relied on reports of households rather than independent observations which potentially made these data less accurate and subject to bias. This applies, for instance, to the physical collection of data pertaining to the weight of fuel used by the households on a regular basis. Though questionnaire data is helpful in this regard, not having supplementary physical measurements limits the accuracy of the information provided by the studies.

### 3.3. Factors influencing fuel stacking and switching patterns

While not an aim or objective of this study, conducting the review provided an opportunity to consider factors that influence fuel use choice, fuel stacking and fuel switching in South African low-income households. These were broadly grouped into energy, geographical, socio-economic, behavioural and temporal factors (Fig. 2). This categorization is similar to what has been presented in other literature where determinants have been grouped according to the COM-B theoretical framework to examine fuels stacking behaviours [8]. The COM-B framework talks to how people's **C**apabilities (psychological and physical), **O**pportunities (social and physical) and **M**otivations (automatic and reflective) interact with each other to influence **B**ehaviour [8]. This includes knowledge, intellectual capacity, decision-making processes, cultural practices and norms, automatic habits, emotions and instincts,

**Table 4**
Overview of the information most frequently requested from participants to help unpack fuel use patterns across all studies.

| Category of influencing factor | Information most frequently gathered |
|---|---|
| Access to electricity | - Whether the household has access to electricity<br>- The type of electrical connection (e.g., formal or informal)<br>- The reliability / quality of the electrical connection<br>- The frequency of electricity cut-offs<br>- Whether the household receives free basic electricity (free electricity provided by the state to help households meet their basic energy requirements)<br>- Information about actions taken to increase efficiency or to reduce the use of electricity |
| Fuel choice | - The type(s) of fuel used (primarily and secondarily) for cooking, space heating, water heating and lighting<br>- Frequency of the fuels used in the household for the various activities<br>- Appliances used for the various activities |
| Expenditure | - Expenditure on specific fuels per month<br>- Percentage of expenditure on fuel in relation to monthly income<br>- Cost of fuel per unit of fuel per month |
| Behavioural factors | - Reason for choosing a specific primary / secondary fuel<br>- Frequency of fuel use<br>- Method of fuel collection / acquisition<br>- Energy habits of children and parents (related to energy saving reasons and methods as well as fuel use patterns)<br>- In intervention studies: Whether there were changes between polluting and clean fuel types at baseline and after intervention implementation<br>- Knowledge of various ignition methods<br>- Aspirational and preferred fuels and stoves<br>- Intervention acceptability<br>- Cultural preferences or stove or fuel use<br>- Information about whether training was provided on how to use a specific fuel or appliance |
| Seasonal and temporal factors | - Fuel use patterns in summer and winter – different fuel used in different seasons<br>- Fuel use patterns throughout the day<br>- Whether solar water heater provides hot water throughout the day / year |
| Stoves | - Type of stove<br>- Acquisition method of stove<br>- Cost of stove<br>- Frequency of use of stove<br>- Quantity of fuel used in stove<br>- Method of ignition in solid fuel stove<br>- Whether a combination of cook stoves was used |
| Socio-economic and demographic factors | - Age<br>- Gender<br>- Ethnicity<br>- Education level<br>- Employment status<br>- Monthly income level<br>- Family size<br>- Household size<br>- Kitchen structural characteristics<br>- Percent income spent on food<br>- Number of rooms<br>- Roofing material<br>- Appliances and electronic devices owned |
| Air quality | - Window opening habits for HAP exposure<br>- Presence of allergens in house<br>- Perceptions of air pollution levels in community<br>- Perceptions of source of air pollution in community<br>- Indoor air pollution risk<br>- Health of specific household members |

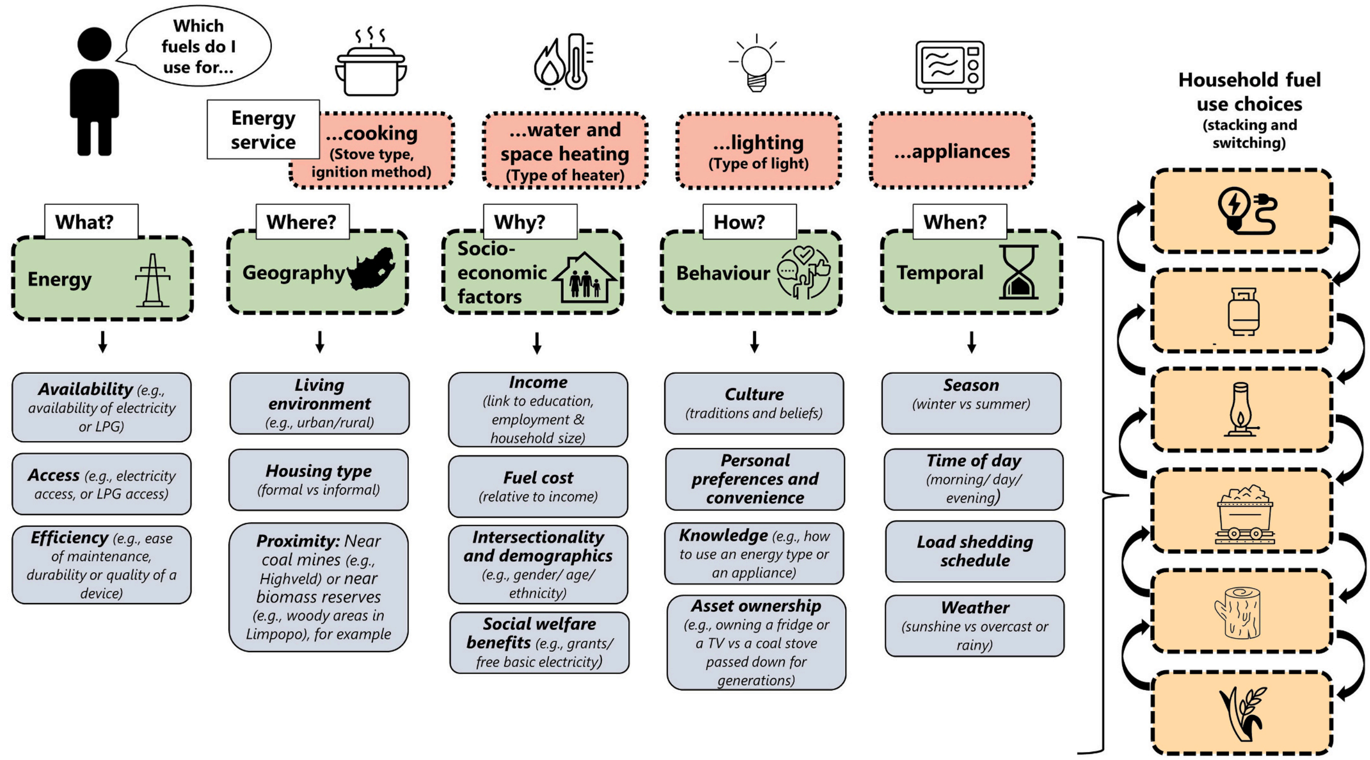


**Fig. 2.** Factors influencing fuel use choices for South African households, based on main themes identified when reviewing the questions asked and the information presented in the reviewed articles.

as well as interactions with our physical and social environment and how these elements all play an important role in influencing behaviour in relation to fuel choice [8].

It is acknowledged that income and the transition of a household from lower to higher levels of socioeconomic development play a large role in influencing fuel choice, but that multiple fuel use is a highly complex, context-specific and non-linear behavioural pattern that can change at any time based on a wide range of reasons [96,97]. Households receiving a pension grant, for example, may if it is within their financial reach opt for electricity for cooking; however, if this is not the case, they may opt for fuels higher on the energy ladder than their previous fuels, stacking up and down the ladder [71]. Two studies specifically mentioned that the successful uptake of an intervention, for example a cleaner cook stove, may simply mean that the household accepts the intervention into its existing stacking habits [49,69]. This may mean that the overall fuel stacking combination of the respective household becomes 'cleaner', even though the household has not fully switched solely to clean fuels.

A large proportion of households in the country are connected to the electricity grid, but high cost of electricity relative to alternative fuels, and the unreliability of the grid necessitates the use of multiple fuels leading to fuel stacking and switching [39,65]. The fuel choice for lighting is less affected by income than for other energy services like cooking or heating as electricity for lighting is efficient and affordable for most households [56].

Cultural dimensions and behavioural factors such as personal preferences, food taste, cooking speed or appliance versatility influence fuel choice and appliance choice too [68]. For instance, wood or kerosene replaces electricity for cooking traditional meals that require longer cooking times like samp (crushed maize), beans and beef tripe and small and soft foods (like eggs or porridge) are cooked using kerosene [47]. In many households, stoves are chosen based on the capacity to cater for large pots to meet a household's large cooking demand. Specific stoves are also known to represent a social status symbol with old and heavy cast iron stoves having been passed on from generation to generation, representing a prized possession which fulfils numerous energy services at once (cooking, space and water heating) [66].

Geographically, much of the country's inland areas are situated on a plateau where it is generally cooler than the coastal areas. This means that most inland areas need space heating in winter thereby promoting the use of solid and traditional fuels like wood and to a lesser extent coal [30]. The availability of energy resources also differs based on location. Spatial differentiation and uneven development in the country, based on historical occurrences, have also led to the unequal distribution of electricity, directly influencing household fuel use patterns [54].

### 3.4. *Implications of fuel use factors for HAP exposure and epidemiological studies*

Information on factors influencing fuel use from the studies' survey questionnaires or other methods provides some meaningful thoughts for application in HAP and epidemiological research. Questions about electricity access can help the researcher deduce whether a household is forced to be reliant on other fuels when electricity is unavailable or too expensive for a household to afford. If a household is unable to afford electricity or does not choose to use electricity, despite having access, a subsidy can help reduce HAP levels by reducing the reliance on dirty fuels like wood or coal [98].

Understanding the fuel stacking or switching patterns of a household can be helpful in determining the severity of HAP exposure. People living in households practicing fuel stacking habits are exposed to higher HAP levels than those living in homes in which clean fuels are used exclusively. This complexity is important and often underplayed in studies in which fuel use is used as a proxy for HAP exposure levels [16].

Asking household members about ignition methods, stove types used or enquiring about the duration of the stove use, can help determine emission factors and exposure times and, to some extent, help understand HAP exposure levels [48]. Including questions about cultural preferences will help identify why households prefer using dirty fuels over clean fuels which again influences HAP levels [48]. Households may at times opt for solid fuels like coal in winter for cooking as coal stoves efficiently retain heat and keep homes warm without incurring extra costs. This two-in-one energy service with a single fuel source is cost-effective, however, it elevates indoor HAP levels.

### 3.5. Consideration of fuel stacking and switching in HAP exposure research

While the reviewed studies referred to the practice of mixed-fuel use in low-income households in South Africa and sometimes indirectly gathered information from which basic fuel stacking / switching habits could be identified (Table A2), only nine of the studies deliberately investigated energy stacking or fuel switching with their research tools. Questions were mainly written to understand main fuels used by households for various energy services, but not necessarily whether fuels used for those same energy services and activities changed over time and why, or to which fuels households shift their usage and for how long. There is a need for more longitudinal, context-specific and nuanced HAP surveys which unpack household fuel stacking and switching patterns considering the multitude of fuels mixed and matched to meet household energy needs. This will lead to more helpful HAP exposure studies [16]. Additionally, if information is only gathered about primary fuels used in a household, important information regarding the possibly polluting secondary or tertiary fuels which are used when stacking and switching, will go unnoticed [25,99]. For example, a household making use of cleaner fuels like electricity 51 % of the time will still experience negative health and social impacts from using polluting fuels like wood or coal 49 % of the time, despite being counted as a household 'mainly using clean fuels' [25]. This is of particular relevance today in the context of load shedding when households are forced to use backup fuels to ensure energy security.

As much information as possible should be gathered about stacking and switching practices from households in a way that is useful to prevent exposure misclassification. Drawing from the reviewed studies, the suggested guidance aims to encourage critical thinking for survey design to better capture fuel switching and fuel stacking habits. Additionally, these suggestions should add value to studies which aim to understand HAP exposure in South African low-income communities from an epidemiological point of view.

#### 3.5.1. Thoughts on methodology for questionnaires and surveys

- Ensure context-specific questions are asked (i.e., ensure questions can be asked in such a way that they cater for responses in low-income and high-income households, for example, to enable comparison).
- Questions about electricity use could be sensitive if the household receives electricity illegally. This is often the case in urban informal settlements [27]. The Statistics SA Household Energy Survey reported that 1 % of households reported to be connected to illegal electricity supply [27].
- Other means of collecting fuel use data could include physical measurements, mapping, body mapping (a visual tool where participants connect their experiences, sensations, or emotions to a specific body area), video diaries, photovoice, theatre and other ways to actively engage participants and community members. This is a way to deepen insights for a more comprehensive understanding [64]. It is important to consider diverse survey techniques (even mixed-method approaches) when collecting data about behavioural aspects to ensure that the method used will successfully access the collective behaviours and societal trends necessary to answer the research questions [100].
- Longitudinal studies, though more costly, improve understanding of energy use changes over time. This represents a large research gap in studies investigating fuel use patterns in South African low-income households.

#### 3.5.2. Improved understanding of fuel stacking / switching and impact on health

- Main fuel use may be clean, but if the household still uses a dirty fuel (as an additional / secondary fuel) then it is not enough to ask about the main fuel to understand exposure or health impacts. It is suggested that questions are asked to identify all fuels used for specific activities. It would be helpful to ask about all energy sources for all major energy services, and to rank as primary, secondary and tertiary, based on frequency of use per season. Asking about fuel use for all possible uses (cooking / heating space and water / lighting / appliances, cooling (especially in times of a changing climate)) to make sure any potential pollution sources are taken into account would be helpful [27].
- There is a need for fuel stacking / switching data in both urban and rural locations for a wide variety of fuel use practices as the dynamics of household energy consumption are complex and vary significantly across different geographical settings [8].
- When assessing the proportion of monthly income spent on fuels, one should recognize that some low-income households incur no fuel expenses at all, either because they source it freely or because they benefit from subsidies. Thus, interpreting fuel use based mainly on income can be misleading [60]. To gain a comprehensive understanding, it is essential to evaluate fuel usage and expenditure through three key measures: 1) the types of fuel used; 2) the actual expenditure on these fuels; and 3) any additional costs associated with transporting the fuel from its source to the household. There are also indirect costs associated with certain fuel use patterns such as time poverty and time burden [101]. While a household might save money by using freely available biomass fuels, the time costs associated with collection and ignition / use can be significant. Recognizing these costs is essential for understanding the full implications of energy choices.
- Questions should also be asked about reasons for the use of the main and alternative fuels. Beyond merely determining if a household has access to electricity (or other fuels) it is important to understand the supply [51]. Inconsistent electricity supply due to load shedding and the overloading of the local network, for example, may force households to use dirty fuels. Due to the consistency of rolling blackouts even into the near future, it might make sense to ask how load shedding influences the fuels that a household uses for heating, cooking and lighting.
- Ask about the source of the fuel, e.g., if a household is burning fuelwood, the type of wood plays a role, as wood burning represents a major source of natural Volatile Organic Compounds (VOCs) [52]. A household can also source discarded wood from a mine or factory which has been treated and which releases VOCs when burning.
- Ask about the type of cooking / heating / lighting device. For instance, if the household is using a clean(er) cookstove or an old polluting coal stove [102].
- It is critical to understand the duration of burning and exposure to gain an understanding of how long a household uses specific fuels for various energy services. It is also important to ask about where the cooking / heating is taking place (will the cooking or heating take place inside or outside of the dwelling? Is it a space where many people are exposed to smoke?).
- Consider including children in longitudinal studies to understand their fuel use patterns as they grow up as this is how fuel use behaviour patterns are potentially perpetuated [61]. The inclusion of questions about how gender could influence fuel choice is important too.
- Sensory experiences with fuel use (including questions linked to smell, taste, vision and feeling) are often omitted from surveys and

should be included to gain deeper insights into the fuels people use (e.g., people may choose wood for cooking as it makes the food taste better, or the smell of using coal has reportedly been linked with poverty) [64]. Additionally, sensory experiences could provide information about health impacts of specific fuel use practices (when using coal for cooking, for example, do people like the smell of the smoke they inhale? If not, why?). Exploring sensory interactions could represent a powerful tool to communicate risks associated with specific fuel use patterns, helping people internalise the negative health impacts of the fuel use, possibly contributing to behavioural change [39].

#### 3.5.3. For studies in which interventions play a role

- Any intervention-based studies in which researchers are trying to either understand whether their interventions are working, or which interventions could possibly work in the specific community (e.g., clean cookstove interventions) should take user preferences and perceptions into account to ensure adoption and sustainable use [66].
- It is critical that potential users of an intervention are asked what they require from a fuel or appliance to accept it and to keep using it [57].
- A study investigating the role of risk communication in the choice and use of unhealthy fuels may be helpful in intervention studies seeking to change behaviour [68].

### 3.6. Policy recommendations and energy transitions

While often sidelined in energy transition dialogues, low-income households with their distinct daily fuel stacking and switching practices influenced by behavioural, socio-economic, geographic, and temporal factors, stand to benefit from tailored policies. Customized, context-specific and people-centred policies can guide low-income households towards optimizing fuel choices and combinations for a clean household energy transition [56].

Examples of such policies applicable to South African low-income households could be subsidies making cleaner energies more affordable [103], as well as the introduction of localized, decentralised renewable infrastructure which can ensure consistent energy provision to reduce reliance on dirty fuels [104]. Educational campaigns teaching household members about the long-term savings and short-term health benefits of using cleaner fuels [106], and seasonal energy solutions, like the introduction of solar heaters for the winter months in heavily wood or coal-dependent communities, could also be helpful. Providing skills training and micro-financing for clean energy solutions at a socio-economic level or introducing community-based energy cooperatives can help uplift the socio-economic status of a household in turn enabling it to use cleaner fuels [103].

Given that women often play a central role in household energy decisions, especially related to cooking, involving them in decision-making processes, training programs, and awareness campaigns and fostering local collaborations can be effective [103]. All of these policy suggestions align with the tenets of practice theory which recognizes the dynamic, context-specific, and socially embedded nature of practices (in this case, fuel use patterns) [105]. By aligning interventions with these principles, the chances of successful and sustainable outcomes increase [105]. Recognizing and addressing these practices can pave the way for these households to transition from being passive consumers to active, instrumental players in the broader clean energy movement at a household level.

## 4. Conclusions

A large proportion of South African citizens living in low-income communities are likely to continue using dirty fuels in their homes in the foreseeable future [37]. Exposure to high HAP levels is therefore predicted to persist in the short term, thereby contributing to the country's disease burden [106]. HAP exposure is highly influenced by fuel use patterns including fuel stacking and switching habits.

Although critical determinants of fuel use patterns such as income, fuel availability and fuel prices play a disproportionately large role in defining what people use to meet their energy needs, more nuanced and context-specific determinants need to be considered to provide powerful insight into HAP exposure studies. Through the lens of HAP exposure, we summarised the findings of 53 South African studies which considered fuel use patterns including fuel stacking and switching practices, in low-income households. Main factors influencing fuel use patterns were access to electricity, location, socio-economic factors, behaviour, and timing. Studies typically did not analyse fuel use habits in a manner that would provide insights into how these patterns impact HAP exposure. We propose recommendations to refine research methodologies so that studies can more accurately characterise HAP exposure in relation to fuel stacking and switching practices.

To define more helpful HAP exposure proxies, it is necessary to understand the complexities that lead to multi-fuel use habits, and to understand the practical nature and details behind this behaviour by asking appropriate questions. This is particularly helpful in cases where physical air quality measurements are not feasible, or to provide context to HAP exposure measurements. The guidance provided here has the potential to significantly enhance the effectiveness of future epidemiological studies on fuel stacking and switching, HAP exposure and human health. This approach is not only crucial for developing more accurate exposure proxies but also pivotal in shaping targeted interventions and policies. This understanding is a crucial stride towards reducing HAP exposure and enhancing the well-being of vulnerable citizens living in low-income communities.

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## CRediT authorship contribution statement

**Bianca Wernecke:** Conceptualization, Investigation, Methodology, Visualization, Writing – original draft. **Kristy E. Langerman:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Alex I. Howard:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Caradee Y. Wright:** Conceptualization, Methodology, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Bianca Wernecke reports financial support, administrative support, and article publishing charges were provided by University of Pretoria.

## Data availability

This is a review article, and no data were collected. However, all information used to write the manuscript has been included in the supplementary material.

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## Appendix A. Supplementary data

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