Harnessing Modern Energy Cooking Services to Mitigate Urban Heat Stress:

A Landscape Study

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Working paper

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About MECS

Modern Energy Cooking Services (MECS) is an eleven-year research programme funded by UK Aid (FCDO). We are a geographically diverse, multicultural and transdisciplinary team working in close partnership with NGOs, governments, private sector, academia and research institutes, policy representatives and communities in 16 countries of interest to accelerate a transition from biomass to genuinely 'clean' cooking.

Executive Summary

Introduction: This landscape study aims to examine how urban cooking practices contribute to heat gains and thermal strain, presenting a scoping review of the existing literature to identify drivers of heat vulnerability and factors contributing to heat loss in cooking technologies. It also evaluates the role of modern energy cooking services (MECS) in mitigating these risks. Despite growing attention to heat in urban studies, the impact of cooking on heat gains and heat vulnerability remains largely overlooked. Traditional cooking methods using biomass and fossil fuels generate both heat and pollutants, worsening indoor and outdoor thermal conditions. This is especially critical in low-income urban environments and informal settlements, where poor ventilation, limited cooling infrastructure, and higher vulnerability converge. MECS emerge as a potential strategy for mitigating these challenges, as modern cooking technologies can reduce heat and pollutant emissions. Yet, gaps persist in quantifying and understanding the thermal impacts of cooking across diverse urban contexts, particularly in socio-economically vulnerable areas. The report concludes by recommending targeted research and policy interventions to unlock MECS's potential for reducing urban heat stress and ensuring more equitable, sustainable living conditions.

Heat stress in urban environments: The frequency, intensity, and duration of heatwaves are increasing globally, particularly in cities in the global South, due to the combined effects of climate change, urbanisation, the Urban Heat Island phenomenon and anthropogenic activities. While most urban studies focus on building design, transportation, and cooling technologies, the heat contribution of cooking often goes unrecognised. Similarly, whilst the literature on health and cooking has significantly focused on indoor air quality and pollutants, limited focus is given to thermal comfort and heat exposure in cooking environments. The cooking sector accounts for 3.5% of global GHG emissions and 58% of building-related emissions, totalling around 1.69 gigatons of CO_2 equivalent. Whilst heat impacts from cooking vary based on cooking fuels, technologies and methods, cooking from biomass and fossil fuels can significantly raise indoor temperatures, increase exposure to pollutants, and intensify local heat loads in densely populated settings. Kitchens are among the most thermally stressed environments within homes, where high temperatures and humidity can lead to health risks ranging from heat exhaustion to heatstroke, reduce labour productivity, and even contribute to global inequality. Although modern cooking appliances like electric pressure cookers (EPCs) generate less residual heat, biomass and fossil-fuel cooking remain prevalent, particularly in low-income and informal urban settlements. Addressing the thermal impact of cooking—and integrating this into broader urban heat mitigation strategies—is essential for building climate-resilient and sustainable cities.

Factors affecting heat vulnerability: Heat vulnerability—i.e. the susceptibility of individuals or populations to the negative impacts of extreme heat—is shaped by a complex set of interconnecting factors that affect how different groups experience and respond to heat stress:

- **Physiological factors**—including age, gender, metabolic rate, and workload—significantly influence heat tolerance. Children, older adults, and individuals performing physically demanding tasks are often at higher risk of heat-related illnesses. Notably, women, who frequently bear greater responsibilities for cooking, often experience hotter conditions with limited access to coping strategies.
- **Socio-demographic factors**—such as income, education, occupation, and social support networks—further determine heat vulnerability. Low-income households commonly depend on inefficient cooking fuels and face limited access to cooling technologies or healthcare. Higher levels of education can increase awareness of heat risks and adoption of preventive measures, yet factors like occupational exposure and social isolation also increase susceptibility.
- **Environmental and spatial factors**—including dense urban infrastructure, inadequate ventilation, and substandard housing—heighten heat exposure. Informal settlements often lack green spaces, insulation, or air conditioning, resulting in higher indoor temperatures. Poor

households in many regions often have only a single indoor space, whereby all household members are unwillingly exposed to the heat generated during cooking, unlike in homes with dedicated cooking spaces. Kitchens in these environments frequently exceed thermal comfort standards, intensifying the likelihood of heat stress.

Measuring heat stress from cooking: Measuring heat stress in cooking environments involves collecting a range of data on **environmental and spatial conditions**, **cooking technology performance**, **socio-demographic factors**, and **physiological responses**. Objective metrics include temperature, humidity, airflow, and cooking energy efficiency, while subjective assessments capture how individuals perceive and cope with heat. Cooking technologies also vary in their heat loss profiles. Solid-fuel stoves and gas cookers can produce substantial residual heat, while modern electric cooking devices (e.g., induction hobs, electric pressure cookers) tend to minimize heat dissipation and reduce exposure times. Additionally, user practices—such as controlling flame intensity, covering pots, and optimizing cooking durations—can significantly lower heat loads and energy consumption. By integrating efficient cooking technologies, improving ventilation, and promoting heat-aware cooking behaviours, households and commercial establishments can substantially reduce kitchen heat stress and enhance overall thermal comfort.

Linking health and heat impacts in cooking: Cooking activities—particularly those involving high temperatures—generate both heat and pollutants that can pose significant health and environmental risks, although the links between heat and pollutant emissions can be complex. In high-heat methods such as grilling or frying, temperatures and cooking duration drive up levels of particulate matter, volatile organic compounds, and polycyclic aromatic hydrocarbons, impacting indoor air quality. Varying temperature and humidity levels can influence how particulates form, disperse, and linger, ultimately affecting occupants' health and comfort. Biomass fuels can emit up to five times more harmful particulates compared to cleaner fuels, heightening both pollution and heat exposure in enclosed spaces. However, both the stove design and combustion process impact efficiency and emissions, underscoring the complexity of managing heat and pollutant trade-offs. Field-based assessments are crucial for fully understanding how cooking methods, fuel choices, and technological improvements intersect with human health and heat stress.

Urban cooking and heat stress: This section presents an overview of the existing literature that links heat stress and cooking in urban environments, focusing on domestic and institutional settings.

Theoretical perspectives on tackling cooking heat stress: This section explores two main theoretical perspectives that can be employed to better understand, analyse and address cooking heat stress. **Social Practice Theory (SPT)** and the **Multi-Level Perspective (MLP)** highlight the socio-cultural and socio-technical dimensions of cooking. These frameworks emphasise the interconnectedness of technologies, behaviours, and societal norms, offering insights into how cooking practices evolve and how interventions can target systemic change. A **feminist lens** underscores the power dynamics and structural inequalities that underpin cooking heat stress, highlighting the implications for the gendered dimensions of cooking and heat vulnerability. Women's disproportionate exposure is rooted in traditional gender roles, socio-economic disparities, and inequitable access to resources. Feminist frameworks advocate for interventions that address these systemic inequalities, promoting gender-responsive technologies and policies.

Leveraging MECS to mitigate cooking heat stress: MECS offer a transformative approach to reducing heat stress in urban cooking environments. By transitioning from traditional biomass and fossil-fuel cooking practices to clean, efficient technologies like EPCs and induction stoves, households, institutions, and commercial kitchens can lower indoor temperatures, enhance health outcomes, and promote urban resilience.

Despite this potential, cooking remains underrepresented in both research and policy frameworks on urban heat stress. Most existing literature focuses on the built environment, transportation, and industrial activities, largely overlooking the heat generated in domestic and institutional cooking settings. Further, health-oriented policies on clean cooking often focus on emissions and indoor air quality, with limited attention to the direct health impacts of cooking-related heat. Addressing these gaps is essential for creating comprehensive and equitable urban heat strategies. Key research priorities include:

- **Quantifying heat contributions of cooking:** Understand how cooking technologies and practices drive heat emissions and evaluate the thermal efficiency of emerging solutions like electric pressure cookers and induction hobs.
- **Evaluating health and gender co-benefits:** Investigate how reduced heat exposure improves well-being, particularly for women and vulnerable groups, and how cleaner cooking transitions can mitigate both indoor air pollution and heat-related health risks.
- **Integration into urban heat mitigation:** Explore how modern cooking solutions can align with sustainable building design and broader urban planning efforts, potentially lowering cooling loads and enhancing thermal comfort.
- **Socio-technical interventions:** Develop gender-responsive adoption strategies, refine cooking efficiency metrics to include thermal comfort, and tailor solutions for institutional and commercial kitchens.

1. Introduction

The intensifying impacts of climate change have brought heat stress to the forefront of global urban challenges. **By 2030, it is estimated that 1.9 billion people will be exposed to heat stress**, particularly in rapidly growing cities (McKinsey Sustainability, 2021). According to the IPCC Sixth Assessment Report, the frequency, intensity, and duration of extreme heat events, including heatwaves, are increasing, with urban areas in the Global South projected to experience the most severe impacts. Increasing urbanisation, together with the phenomenon of the Urban Heat Island (UHI) effect— where urban areas are significantly warmer than their rural counterparts due to factors such as reduced vegetation, increased built surfaces, reduced open and green spaces, and anthropogenic heat emissions— exacerbates the risks associated with extreme heat (Chapman et al., 2017). **Studies estimate that by 2050, UHI related warming will be, on average, about half, and sometimes up to two times, as strong as that caused by greenhouse gas (GHG) emissions** (Marcotullio et al., 2021). In cities across Asia and Africa, super- and ultra-extreme heatwave conditions— which involve **temperatures up to 56 °C and higher**— across extended durations (up to several weeks), are becoming more frequent, leading to substantial public health risks and rising fatalities (WMO, 2024; Zittis et al., 2021).

While much of the existing research on urban heat stress focuses on the role of built environment characteristics, such as building density, lack of green spaces, and impervious surfaces (Chapman et al., 2017; F. Li et al., 2024), there has been relatively little attention paid to the contribution of anthropogenic heat sources like cooking. **Cooking, a ubiquitous daily activity, plays a significant yet often overlooked role in contributing to indoor and outdoor heat.** Traditional cooking practices, particularly those reliant on biomass and fossil fuels, generate substantial pollutant and heat emissions, whereby the latter can exacerbate indoor thermal conditions and elevate temperatures in densely populated urban areas. Moreover, many urban kitchens, particularly in low-income and informal settlements, frequently operate with poor ventilation, leading to heat accumulation that intensifies thermal discomfort and health risks (Okore et al., 2022).

Studies also show that heat vulnerability is not evenly distributed (Burke et al., 2015; Green et al., 2019; Marcotullio et al., 2021). Equatorial countries are exposed to higher heat stress than higher latitude countries (Parkes et al., 2022). About half of the future urban population, primarily in the tropical global South, will experience extreme heat risks due to urban expansion-induced warming (Marcotullio et al., 2021). Estimates show that exposure to high-index heat wave with UHI can impact over 55% of Africa's population by 2100. Currently, most of the populations exposed to very warm heat waves are living in low-income countries (countries with GDP per capita at or below $4,000) (Marcotullio et al., 2021). **Exacerbating heat stress resulting from urbanisation processes and climate change will have larger impacts on such low-income countries with little capacity to adapt to rising temperatures** (Chapman et al., 2017; IPCC, 2023). **Some of the highest impacts of extreme heat will be faced by South Asian countries, making many regions uninhabitable by mid-century** (Im et al., 2017). **In Africa, studies estimate that exposure to "dangerous heat" (exceeding 40.6 ◦C) will increase 20 to 52 times, with cities in Western Africa facing the highest concentration of exposure** (Rohat et al., 2019). Population growth and urbanisation in many megacities in the global South can cause temperatures in their urban core to be up to 10°C higher than those in the surrounding rural areas (ILO, 2019). Whilst urban residents are exposed to higher heat stress risks than rural residents, urban heat exposure can have distributional impacts that vary across geographies, regions, cities and even neighbourhoods.

There is substantial evidence that extreme heat can result in both increased deaths and illness. In mapping community vulnerability to heat stress, Reid et al. (2009) show substantial spatial variability in heat vulnerability, connected with socio-demographic factors like poverty, income, age, health and environmental factors, including vegetation cover. Within urban areas, they find that **inner cities** showed the highest vulnerability to heat. Acknowledging that **not all populations will be at equal health risk** from heat stress is critical. Further, heat stress and increasing temperatures can also exacerbate existing inequalities and have greater implications for more low income and vulnerable populations (Waha et al., 2017). Increasing urbanisation and rural-to-urban migration can put additional strains on low-income urban neighbourhoods and precarious infrastructures. Therefore, recognising and understanding intersectional differences in vulnerability to heat stress, both socially and spatially, can be important for mapping and for targeting interventions.

The contribution of cooking to heat stress is particularly significant in low-income urban areas, where fuel stacking and the use of unclean fuels remain prevalent (Butera et al., 2016; Okore et al., 2022). These settings often lack adequate ventilation or cooling infrastructure, resulting in higher exposure to heat and pollutants. Yet, the intersection between cooking, heat stress, and urban environments remains an underexplored area in current urban heat research. Studies predominantly focus on outdoor sources of anthropogenic heat like transportation, leaving a substantial gap in understanding how indoor activities like cooking contribute to urban thermal stress, particularly in developing areas, low-income and informal or slum settlements where residents already face heightened vulnerability.

This report aims to address the critical gap in the existing literature by exploring the role of cooking practices and technologies in contributing to urban heat stress. The objectives are threefold:

- To highlight cooking as a significant, yet under-recognised, contributor to urban heat stress.
- To explore how modern energy cooking services (MECS) can serve as a mitigation strategy to reduce heat stress, particularly in developing economies and low-income urban settings.
- To identify critical research gaps and propose a research agenda that focuses on leveraging MECS for reducing heat stress.

The report is structured as follows: Section 2 delves into the broader issue of heat stress in urban environments, examining the role of anthropogenic heat sources and highlighting the often-overlooked contribution of cooking to heat accumulation. Section 3 focuses on the various factors affecting heat vulnerability, discussing the physiological, socio-demographic, environmental, and spatial determinants that influence how different populations experience heat stress. Section 4 discusses methods for measuring heat stress from cooking, including an overview of the thermal performance of different cooking technologies and the linkages between health and heat impacts in domestic settings. Section 5 presents a review of the literature on urban cooking and heat stress, mapping thermal comfort in domestic and institutional settings, and comparing the impacts of electric and gas cooking. Section 6 explores different theoretical perspectives on tackling urban heat stress through MECS, addressing the socio-technical dimensions of clean cooking. Section 7 concludes with recommendations on how MECS can be leveraged to reduce heat stress in urban areas, identifies existing gaps in the discourse, and outlines future research avenues.

2. Heat stress in urban environments: anthropogenic heat and the overlooked role of cooking

Heat stress has emerged as a critical challenge facing urban areas, particularly in the context of climate change and rapid urbanisation. The frequency, intensity, and duration of heatwaves are increasing globally, with cities in the Global South projected to experience the most severe impacts due to the combined effects of the UHI phenomenon and anthropogenic heat sources (IPCC, 2023; McKinsey Sustainability, 2021). **Anthropogenic heat—heat generated from human activities such as transportation, building climate control, mechanisation and industrial processes—significantly contributes to the UHI effect** (Mirabi and Davies, 2022), making cities hotter than their surrounding rural areas. As urban populations grow, the intensity of anthropogenic heat release is expected to rise, further exacerbating urban thermal conditions. Urban studies have primarily focused on the built environment, building design and passive design strategies to mitigate heat stress in urban environments, while some focus has also been given to interventions in transportation and cooling technologies (Parkes et al., 2022) as key sources of urban heat. However, **the contribution of cooking to the overall heat load in urban environments is often overlooked.** Similarly, whilst there is an extensive literature looking at indoor air quality and pollutants in kitchen within the field of health and environmental sciences (e.g., Champion et al., 2021; Domingo, 2010; Giwa et al., 2022; Pope et al., 2015; Willers et al., 2006), less focus has been given to thermal comfort, specifically investigating the levels of heat exposure and resulting heat stress in cooking environments.

Cooking-sector emissions account for about **3.5% of global greenhouse gas (GHG) emissions** and **58% of emissions from buildings** (UNDESA, 2023). In 2020, total emissions from the cooking sector were estimated at **1.69 gigatons (Gt) of Carbon dioxide equivalent (GtCO2e)-** three times higher than aviation emissions during the same (pandemic) year (Graver et al., 2020).The use of biomass and fossil fuels for cooking, particularly in the global South, leads to significant heat generation, which not only contributes to thermal strain but also releases pollutants that exacerbate local air quality issues (Garland et al., 2017; Kadian et al., 2007). Notably, **black carbon**—commonly known as soot, which is a component of PM2.5 particulate emission and a byproduct of incomplete combustion—has a warming impact up to 1,500 times stronger than CO_2 per unit of mass, further intensifying the local heat load (CCA, 2023). According to the Clean Cooking Alliance (2023), domestic cooking, heating, and lighting (from fossil fuel sources like kerosene) together account for about 25% of global black carbon emissions, whereas in Asian and African countries, household cooking can account for as much as 60%-80% of black carbon emissions. Black carbon is considered a short-lived particle, but it has a very high global warming potential (GWP) and causes significant short-term, regional climate impacts (Garland et al., 2017).

Figure 1: Smoke and heat emissions from biomass cooking in urban informal settlements, India (Source: Finovista)

Just as the GHG emissions and climate impacts from cooking processes depend on a complex set of factors, including the fuel sourcing, appliance manufacturing, Life Cycle Assessments, sustainable harvesting, and net carbon emissions etc. (Wright et al., 2020), so do the **heat impacts from cooking vary based on the cooking fuels used, technologies employed, methods chosen and practices undertaken. Cooking with biomass fuels like wood and charcoal releases substantial heat and pollutant emissions**, which can accumulate in indoor environments, especially where ventilation is poor. In many low-income and informal urban settlements, households rely on inefficient stoves and fuels (Boateng and Adams, 2022; Butera et al., 2016; Kansiime et al., 2022), which release not only GHGs but also significant amounts of heat into living spaces (Adegun, 2024). **Even cleaner fuels like natural gas and LPG, as fossil fuels, emit GHGs with CO_2 emissions of roughly half that of coal for the same amount of heat energy** (Wright et al., 2020). The heat generated by cooking activities raises indoor temperatures, often by several degrees Celsius, particularly in confined spaces. For instance, studies by Luo et al. (2023) show that gas cooking can raise kitchen air temperatures by 8-9°C even with exhaust ventilation, while Rahman et al.'s (2014) air flow dynamic simulations showed kitchen temperatures reaching up to 54°C without mechanical ventilation.

Research indicates that **kitchens are among the most thermally stressed environments within homes**. According to Simone et al. (2013), temperature variations in kitchens can reach up to 10°C above ambient levels, with radiant heat from cooking appliances further increasing the operative temperature by an additional 5.8°C. This increase is particularly problematic in densely populated urban areas where mechanical ventilation is limited. Kitchens in these settings frequently exhibit elevated humidity levels, as noted by Giwa et al. (2022), who found that Relative Humidity (RH) levels during cooking averaged around 68%, significantly raising the heat index and heightening the risk of heat-related illnesses.

The thermal discomfort associated with cooking is not just a matter of indoor air temperature but also involves other factors such as relative humidity, radiant heat, and airflow. **The combination of high temperatures and humidity can lead to thermal strain**, causing health issues like heat exhaustion, heat cramps, and in extreme cases, heatstroke (Haruyama et al., 2010). If this thermal strain is not controlled, it can lead to critical illnesses and consequences such as headache, heat shock, heat fatigue, thermal syncope (dizziness or fainting), physical and mental impairment, neuropsychiatric symptoms, decreased consciousness and perception, and even death (Yazdanirad et al., 2020). The use of solid biomass fuels for cooking has been shown to have both adverse health impacts, while also hindering thermal comfort, and even leading to thermal strain, resulting in a lower quality of life (Ravindra et al., 2019). Further, elevated temperatures in the cooking environment are not only related to inducing heat stress among cooks but can also lead to harming food products by being exposed to elevated temperatures in the 'danger zone' (between 5-60 °C) that facilitate the growth of microorganisms causing food-borne illnesses (NSW, 2020).

Figure 2: Cooking with firewood in the Rohingya refugee camps, Cox's Bazar Bangladesh. (Source: Rafa et al., 2024)

Other studies (e.g., Singh et al., 2016) also highlight that prolonged exposure to high-temperature cooking environments can affect productivity and overall well-being, especially in urban settings where space is constrained. **Temperatures above 24–26°C are associated with reduced labour productivity.** The ILO (2019) estimates that by 2030, more than 2% of total working hours worldwide is projected to be lost every year, either because it is too hot to work or because workers have to work at a slower pace. At 33–34°C, a worker operating at moderate work intensity loses 50% of their work capacity. This loss is also seasonal, and unevenly distributed geographically. In Southern Asia and Western Africa, the resulting productivity loss may even reach 5%, as a result of increasing heat events combined with densely populated areas, high rates of agriculture, high rates of informality and vulnerable employment. Further, **the economic burden of heat-related labour loss is projected to reach 2400 billion USD by 2030** (ILO, 2019). Moreover, studies suggest that warming may amplify global inequality with hot, poor countries potentially suffering largest reductions in growth (Burke et al., 2015).

Whilst the evidence noted above suggests that heat from cooking will be an added burden to many regions, resulting in high heat exposures and thermal strain, it is important to acknowledge that cooking and heating needs can also be interwoven, especially in colder, higher-altitude regions. Some studies, for example, have shown how poor residents in informal settlements use the same unclean fuels for cooking and heating purposes, particularly during colder months (Kovacic et al., 2019). In such contexts, cooking heat is often viewed as desirable (Okore et al., 2022) and does not result in heat stress. Although this scenario falls outside the primary focus of this report, it underscores prolonged exposure to polluting emissions, which carries significant health implications. This highlights the necessity of distinguishing between heat for cooking and heat for keeping warm, which has critical implications for policy and the design of technologies and interventions. Notably, some studies (Khalid et al., 2024) indicate that with the introduction of clean energy interventions, heating fuels have been successfully switched to cleaner, more affordable alternatives, thereby breaking the reliance on shared cooking and heating fuels.

Daily cooking processes and food-related practices are energy-intensive activities in typical households in low- and middle-income regions (Wright et al., 2020). While electric cooking appliances like Electric Pressure Cookers (EPCs) and kettles can be energy-intensive over short periods of time, they are overall very efficient. Even more energy is utilised in fossil-fuel based cooking because of the inefficiencies associated with converting biomass energy to useful heat for cooking. As a result, significant heat is generated and dissipated into the environment in biomass and fossil-fuel cooking. Whilst biomass cooking is still prevalent across rural areas in low- and middle-income regions, biomass fuels still form a significant part of the fuel mix in urban areas as well (Figure 3 and Figure 4), particularly in Sub-Saharan Africa (Stoner et al., 2021).

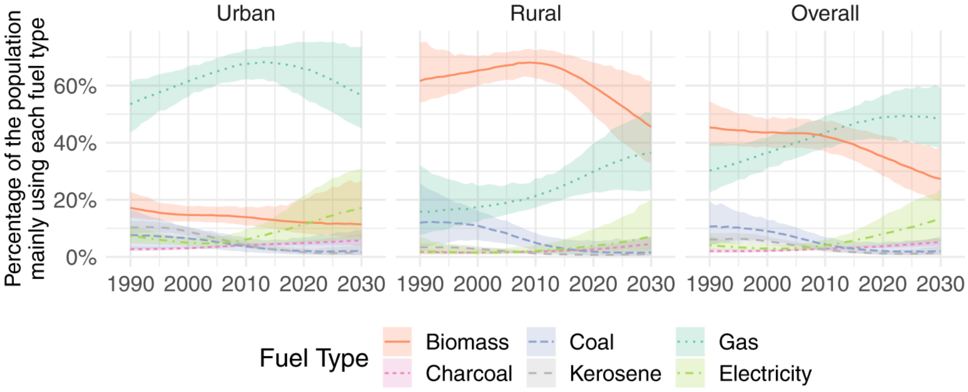

Figure 3: Estimated percentage of the population in Low- and Middle-Income Countries mainly using each fuel type. (Source: Stoner et al., 2021)

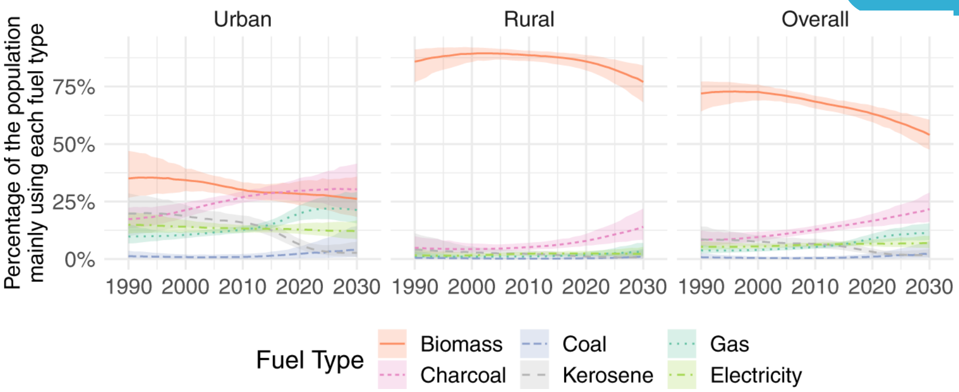

Figure 4: Estimated percentage of the population in Sub-Saharan Africa mainly using each fuel type. (Source: Stoner et al., 2021)

Useful definitions

Heat Stress: Heat stress refers to the build-up of body heat generated either internally by muscle use or externally by the environment. It occurs when the heat a body absorbs from the environment exceeds the body's ability to dissipate it. The external heat build-up in the human body is due to air temperature, wind speed, water vapour pressure and short- and long-wave radiant fluxes (ECMWF, 2024). Heat stress is resultant of the net heat load to which a worker is exposed. Physical exertion, metabolic heat, environmental factors, and clothing worn all contribute to heat stress.

Heat/Thermal Strain: Thermal strain is the human body's physiological and psychological response to heat stress or the body's measurable changes in function and performance due to heat exposure (Yazdanirad et al., 2020). When exposed to extreme heat, the body responds to dissipate excess heat through changes in the heart rate, core body temperature, skin temperature, and sweating rate. This is the body's natural way to keep the core body temperature from rising to unhealthy levels. When these are not enough to keep the core body temperature from rising, the result is heat-related illness or death. Elevated core body temperatures may cause heat stroke, heat exhaustion, heat cramps, heat syncope (fainting or dizziness), heat rash and rhabdomyolysis (muscle breakdown) (Yazdanirad et al., 2020).

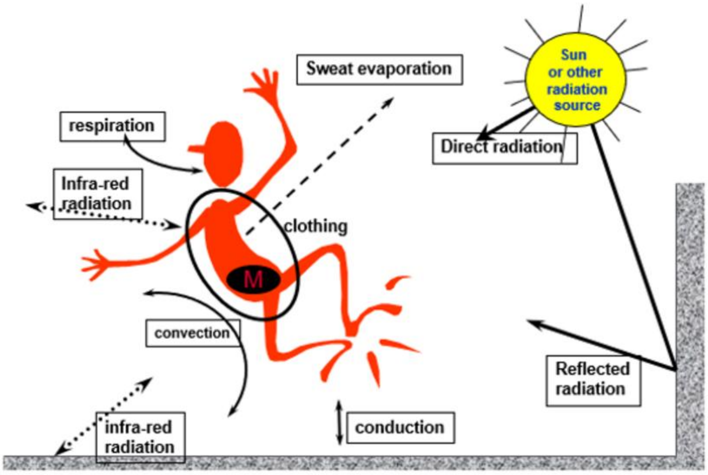

Figure 5: Heat exchange and the human heat budget (M = metabolic heat production) (Source: Havenith, 2001 and ECMWF, 2024)

(continued…)

Urban Heat Island (UHI) Effect: The phenomenon where urban areas are significantly warmer than their surrounding rural areas. This is generally the result of human activities, dense building structures, limited vegetation, and heat-retentive surfaces like concrete and asphalt. The UHI effect can raise nighttime temperatures and intensify heat stress in cities (IPCC, 2023). In addition to the complex urban landscape, the heat generated by heating, cooling, transport, and other energy uses, like cooking, also contribute to UHI.

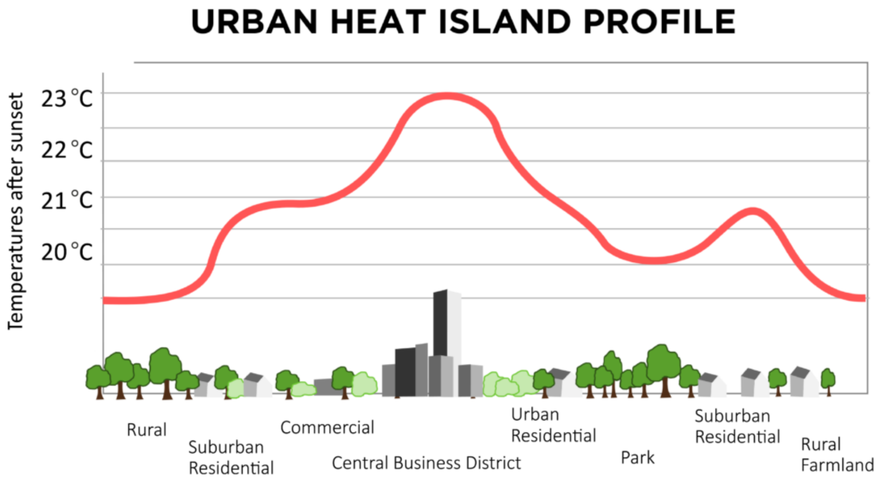

Figure 6: The Urban Heat Island (UHI) effect in different density profile areas (Source: MetLink, Royal Meteorological Society)

Heat vulnerability: The degree to which individuals or communities are at risk of experiencing negative health outcomes due to heat exposure. Heat vulnerability is influenced by a number of different environmental, socio-economic, geodemographic and physiological factors (Karanja and Kiage, 2021), including age, gender, socioeconomic status, housing conditions, access to cooling resources, and pre-existing health conditions.

An understanding of vulnerability should encompass (Parry et al., 2007):

- Exposure: How much a person is exposed to high temperatures inside and outside
- Sensitivity: How sensitive a person is to heat
- Adaptability: How well a person can adapt to high temperatures

Heat vulnerability can be assessed using heat vulnerability indices (Manware et al., 2022), which combine data points like race, ethnicity, building density, and air temperature anomalies. These indices can help researchers and municipalities identify areas at high risk and plan interventions.

Despite the clear link between cooking and heat generation, the current urban heat stress literature largely overlooks the role of household and institutional/commercial cooking in contributing to indoor and outdoor heat loads. Most urban studies focus on transportation, building materials, and cooling technologies, often neglecting the micro-environmental impacts of cooking activities (F. Li et al., 2024; Parkes et al., 2022). This oversight is significant, given that kitchens are typically among the most thermally stressful areas within homes and other buildings, particularly in regions where traditional cooking methods remain prevalent.

Whilst there is extensive research on indoor air quality related to kitchen pollutants, studies specifically examining thermal comfort and heat stress in cooking environments are scarce (Wright et al., 2020). Understanding the thermal dynamics of cooking and the role of different cooking technologies is crucial for developing interventions that can contribute to mitigating urban heat stress. As cities continue to expand, addressing the thermal impact of cooking in both formal and informal settlements will be essential for enhancing urban resilience to heat stress.

3. Factors affecting heat vulnerability

The IPCC defines vulnerability as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change (Parry et al., 2007). **Heat vulnerability specifically refers to the susceptibility of individuals or populations to the negative impacts of extreme heat.** Whilst there is no single index of heat stress that has been universally accepted (Yousef et al., 1986), scholars generally are in agreement that **heat vulnerability is shaped by a complex interplay of environmental, physiological, socio-demographic, and spatial factors** that influence how different groups experience and respond to heat stress. As Marcotullio et al. (2021) argue, **vulnerability is a function of the intensity, exposure, sensitivity, and adaptive capacity of populations to extreme heat events.** Additionally, socio-economic and political contexts, such as access to resources, healthcare, and public infrastructure, play a crucial role in determining the degree of exposure and capacity to cope with heat (O'Brien et al., 2007). This section outlines the various factors that contribute to cooking heat stress, as illustrated in Figure 7. The technological characteristics are covered in detail in Section 4.1.

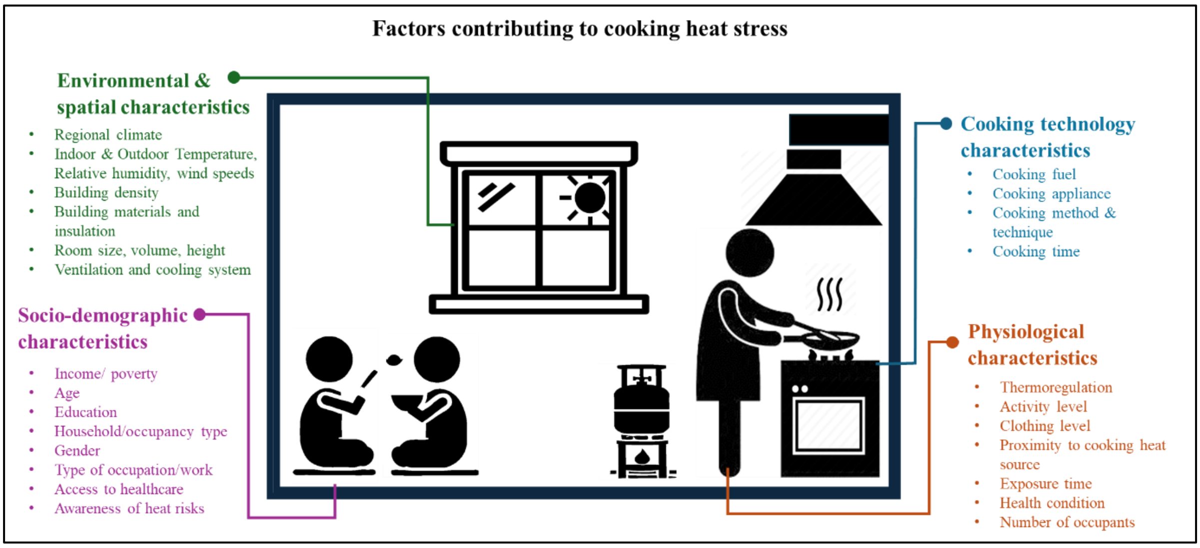

Figure 7: Various environmental, spatial, socio-demographic, technological and physiological factors contributing to cooking heat stress (Source: Author).

3.1. Physiological characteristics

Physiological factors significantly affect an individual's ability to tolerate heat stress. Individual tolerance to heat can vary significantly and is influenced by a range of physiological and contextual factors, including age, gender, acclimatization and duration of exposure (Yousef et al., 1986). For example, studies show that **young children and older adults, especially those over 65, are particularly vulnerable** due to diminished thermoregulatory capabilities and pre-existing health conditions that exacerbate heat-related risks (Glass et al., 2015; Reid et al., 2009).

Differences in heat tolerance can also be influenced by sex and gender. Studies have shown that **females, on average, exhibit lower levels of perspiration and heat tolerance, and a higher heart rate and rectal and skin temperatures** compared to males, particularly under conditions of physical work, making them more susceptible to heat stress (Yousef et al., 1986). Studies (e.g., Glass et al., 2015; Mukhopadhyay and Weitz, 2022) have also found that elderly women are more likely to experience dangerous heat index levels (i.e., heat indexes > 45 °C) and report multiple heat-related symptoms compared to men. In these studies, differences in symptom frequency, number and severity were related to gender differences in heat stress, as elderly women were exposed to significantly hotter conditions during the day. Women's higher heat exposures can also be related to their reduced access to coping strategies. Elderly women were significantly less likely than elderly men to change or remove clothing, alter or reduce social activities, avoid or reduce household/economic activities, or to take a bath or shower. Further, more elderly village women reported being active all day compared to elderly village men (Mukhopadhyay and Weitz, 2022); nevertheless, even when compared with similarly aged outdoor-active elderly men, elderly women experienced greater heat strain (Glass et al., 2015). **Gender also becomes significant in relation to cooking, since gender appears as the single most impactful predictor of the frequency of home cooking**, with women estimated to cook as many as **4.3 more meals per week than men** on average, with all other factors being equal (Gallup, 2023).

The body's ability to regulate temperature can also be influenced by factors such as metabolic rate, clothing, workload, and activity level. Individuals employed in physically-demanding occupations are also at-risk for developing heat-related illnesses (Ierardi and Pavilonis, 2020). For instance, cooking can involve varying intensities of physical activity (light, moderate or heavy workload), contributing to increased metabolic heat generation (Ierardi and Pavilonis, 2020).

Ierardi and Pavilonis (2020) provide a calculation for the Action Limits (AL) and Threshold Limit Values (TLV) for heat stress for kitchen workers, expressed in terms of the Wet Bulb Globe Temperature (WBGT), based on the American Conference of Governmental Industrial Hygienists' (ACGIH) established criteria to protect workers from heat stress (OSHA, 2017), as shown in Table 1. These values vary according to factors like workload and metabolic rate, aiming to keep the core body temperature within one degree Celsius of normal. **The Action Limit indicates the temperature at which an un-acclimatized worker may experience a potential health effect from heat exposure**, whereas the TLV represents the recommended limit for a heat-acclimatized worker. This may, however, leave unacclimatized individuals, such as household cooks or informal workers, at greater risk of heat-related illnesses.

Table 1: Action Limits and Threshold Limit Values for heat stress for three metabolic work-rate scenarios (Source: Ierardi and Pavilonis, 2020)

Metabolic Work-Rate (W)	Classification*	Action Limit	TLV
180	Light	28.1	30.8
300	Moderate	25.0	28.2
415	Heavy	23.0	26.6

* as per OSHA Heat Hazard Assessment (OSHA, 2017)

The physiological impacts of heat exposure in cooking environments have been documented in several studies. Anua et al. (2021) examined physiological changes among 30 cooks in food stalls and cafeterias in Kelantan, observing significant increases in core body temperature and heart rate from pre-shift to post-shift. Although no direct correlation was established between physiological changes and specific heat exposure levels, the majority of participants reported heat-related symptoms, including fatigue, dizziness, irregular movement, and nausea. This **underscores the importance of considering not only objective physiological metrics, such as age, sex and metabolic rate, but also subjective experiences of thermal strain when assessing heat stress**. For instance, individuals performing physically demanding tasks during cooking in confined or poorly ventilated spaces are more likely to experience thermal discomfort and related health symptoms (Haruyama et al., 2010).

Similarly, Melaku et al. (2024) conducted a study on 605 hospitality kitchen workers in Ethiopia and found that over 67% experienced heat stress symptoms. Contributing physiological factors included older age (≥ 40 years), although other factors also played a role, including poor heat mitigation practices, reliance on wood fuel, inadequate ventilation, and higher heat index values, which will be discussed in the following sections.

3.2. Socio-demographic characteristics

Socio-demographic factors, including age, gender, income, education level, and occupation, shape heat vulnerability in significant ways. Socio-demographic measurements provide contextual information that helps identify vulnerable groups who may be more susceptible to heat-related health impacts due to their societal/socio-economic roles and physical conditions. **Low-income households are particularly vulnerable** due to limited access to clean fuels and technologies, proper ventilation, adequate spatial infrastructure, healthcare, and other adaptive measures (Okore et al., 2022). Previous studies have shown that households with more family members engaged in paid employment tend to have higher incomes and are more likely to use cleaner cooking energy sources (Ishengoma and Igangula, 2021; Kitole et al., 2023). This correlation between household income and the adoption of modern, cleaner fuels suggests that economic status directly impacts the ability to mitigate heat stress. However, even with increased income, the persistence of fuel stacking—using multiple types of fuels—suggests that **economic factors alone are insufficient to mitigate heat vulnerability.**

Education also plays a crucial role. Individuals with higher levels of education are generally better informed about the risks associated with heat and are more likely to adopt preventive measures. For instance, Mukhopadhyay and Weitz (2022) found that individuals with post-secondary education reported fewer heat-related symptoms, such as fatigue, dizziness, and heat cramps, compared to those with lower educational attainment.

In addition, occupational exposure to heat remains a significant issue. **Individuals employed in physically-demanding occupations,** such as kitchen staff, construction workers, and street vendors, and/or those who work in hot, humid environments for extended periods of time **are considered particularly at-risk** for developing heat-related illnesses (Ierardi and Pavilonis, 2020). For example, kitchen workers have been shown to experience a high incidence of heat-related symptoms such as heat exhaustion, fatigue, irregular movement, dizziness, nausea, muscle spasm, and fainting (Melaku et al., 2024). Among kitchen workers, **higher thermal strain has also been associated with greater age (≥55 years), years of employment (≥3 years), working hours (≥8 hours), regular occupation, and type of cooking job**, in addition to other spatial characteristics (Haruyama et al., 2010). Moreover, social isolation and living alone can increase vulnerability (Tong et al., 2021), particularly among the elderly, who may lack the social support needed to cope with extreme heat (Reid et al., 2009). **Vulnerable populations, such as women, children, and the elderly, are disproportionately affected by heat** due to their social roles, limited mobility, or access to resources (Green et al., 2019).

3.3. Environmental & Spatial characteristics

The physical environment and spatial characteristics of urban areas significantly impact heat exposure. **Regions with hotter climates or those experiencing increased frequency of heatwaves due to climate change face higher heat vulnerability**. Populations not accustomed to extreme heat are also at risk when unexpected heatwaves occur (Hajat et al., 2007). According to the ILO (2019), **populations in urban areas in tropical and subtropical developing countries are worst affected by rising heat levels** due to a combination of high baseline temperatures, dense populations and existing vulnerabilities. Heat vulnerability levels are highest among **lowest-income groups**, in particular agricultural workers, small-scale and subsistence farmers, and casual workers. **Urban areas tend to be hotter than rural areas** due to dense infrastructure, limited green spaces, and heat-absorbing materials like asphalt and concrete (Chapman et al., 2017), intensifying the heat exposure for residents. **Urban density is a key factor in the spatial variability of the UHI**, and higher temperatures often occur in the densest parts of the city, exposing residents in these areas to high heat stress (Chapman et al., 2017). The densest parts of the city are often those with low-income populations, informal settlements, and more precarious infrastructure, leading to increased vulnerability to heat.

Housing conditions play a critical role in determining heat vulnerability. In their study of heat exposure in urban and rural India, Mukhopadhyay and Weitz (2022) reveal that heat coping strategies were found to be associated less with Heat Index measurements and heat-related symptoms, and more with the site location, i.e., residents of slum developments and rural villages were found to be more vulnerable to heat stress. In addition, the construction material of the dwelling, the size and room number of dwellings, as well as personal and/or behavioural characteristics (such as gender, activity, education, etc.) provided the greatest number of significant predictors to heat stress. As noted by Weitz et al. (2022), in informal settlements and slums, construction materials and the UHI effect combine to create hotter indoor than outdoor conditions throughout the day, and particularly at night, making **residents in urban slums over four times more likely to experience dangerous heat index levels (≥ 45°C), compared to rural residents**. Tong et al. (2021) demonstrate that heat vulnerability is increased by the degree of exposure to heat, and subsequently link this with spatial characteristics, including living in heat island neighbourhoods, lack of tree cover, lack of air conditioning, living on upper floors of buildings, and working outdoors.

Kitchen spaces themselves play a critical role in determining heat dissipation and thermal comfort, with their design, purpose, and location significantly influencing indoor thermal conditions. Kitchen configurations can vary widely across regions and socio-economic groups, reflecting differences in cultural practices, architectural traditions, and access to resources. For instance, household kitchens may include closed, designated spaces that separate cooking activities from other household functions, while in lower-income settings, cooking often occurs in multi-purpose rooms shared with other activities or even outdoors (Khalid and Sunikka-Blank, 2018). **Outdoor kitchens, prevalent in warmer climates or rural areas, offer better heat dissipation but are subject to other environmental constraints, such as weather exposure** (Adegun, 2024; Kansiime et al., 2022). These variations underscore the importance of considering the type and purpose of kitchen spaces when evaluating thermal comfort and heat stress in cooking environments. Commercial kitchens, on the other hand, are designed to handle larger-scale operations but exhibit substantial diversity in size, layout, and technology, depending on their specific functions, such as fast food, casual dining, or institutional catering. This further complicates an evaluation of their indoor thermal environment, as highlighted by Simone et al. (2013). **Thermal conditions and susceptibility to heat stress can vary significantly based on the type of kitchen space** (casual restaurant, institutional restaurant, or quick-service restaurant), the various activities being performed (preparation, cooking, dish washing), the building design and construction, and type of HVAC system installed (e.g., level of insulation, number of windows, air conditioning, natural ventilation etc.).

4. Measuring heat stress from cooking

Cooking activities significantly contribute to heat accumulation in kitchen spaces through several thermal processes. ***Sensible heat*** (i.e. heat energy that causes a change in the temperature) is generated by cooking appliances such as stovetops and ovens which emit thermal energy that directly increases the ambient air temperature. ***Latent heat*** (i.e. energy absorbed or released when a substance changes state) occurs when moisture is added to the air, for instance when water and other liquids used in cooking evaporate, increasing both humidity and perceived warmth. **Radiant heat** is emitted from hot surfaces and open flames in the form of infrared radiation, transferring energy directly to occupants and objects without necessarily heating the intervening air. **Combined, these forms of heat elevate temperatures/humidity levels within the cooking space** and can permeate adjacent rooms, especially in environments with open floor plans or inadequate ventilation. This can lead to discomfort, increased thermal stress, and a reliance on cooling systems, particularly in summer season and warmer climates. **In commercial and institutional kitchens, the effect is magnified due to larger-scale operations and prolonged cooking periods**, resulting in significant heat buildup that affects workers' well-being and adds to the overall thermal load of the building (Ierardi and Pavilonis, 2020; Melaku et al., 2024; Singh et al., 2016).

As indicated by the various factors affecting heat exposure and vulnerability, **measuring heat stress in cooking environments involves an integration of various parameters across environmental,**

spatial, technological, social, and physiological domains (Figure 8). These measurements enable a comprehensive evaluation of heat exposure during cooking and its impact on individuals. Importantly, heat stress is not only a function of the objective thermal environment but is also shaped by the subjective experiences of the occupants, thereby requiring the incorporation of both objective metrics (e.g., temperature, humidity, and energy efficiency) and subjective assessments (e.g., personal perceptions of comfort and thermal sensation).

4.1. Environmental and Spatial Measurements

For assessing the physical conditions of the cooking environment that can contribute to heat stress, environmental monitoring is required together with an understanding of spatial factors. **Environmental monitoring typically includes the collection of climate data, such as outdoor temperature, relative humidity and wind speed, in addition to indoor environmental monitoring of temperature, humidity, air quality, and airflow**. The use of data loggers allows for continuous monitoring of these variables, providing a detailed understanding of thermal variations within the cooking environment. Some studies (e.g., Anua et al., 2021) employ a **Wet-Bulb Globe Temperature (WBGT)** to assess heat stress risks by combining air temperature, humidity, wind speed, and solar radiation into a single index. WBGT measurements are especially useful in outdoor environments as they include measurements of radiant energy from direct sunlight (OSHA Technical Manual (OTM), 2017).

Other studies (e.g., Giwa et al., 2022; Haruyama et al., 2010; Melaku et al., 2024; Mukhopadhyay and Weitz, 2022) have also employed a **Heat Index (HI),** also known as the apparent temperature, which helps to assess heat stress risks by indicating conditions under which the body may struggle to dissipate heat effectively, potentially leading to heat-related illnesses like heat exhaustion or heat stroke. The HI combines air temperature and relative humidity to provide a better indication of thermal perception, reflecting how hot it feels to the human body (NOAA, 2016; OTM, 2017). Humidity effects the body's ability to cool itself through sweating, as higher humidity levels make it harder for sweat to evaporate, leading to an increased perception of heat (Rothfusz, 1990).

Spatial variability is another critical consideration, as heat distribution within a kitchen may differ vertically and horizontally (Luo et al., 2023; Rahman et al., 2014; Zhang et al., 2021). Factors such as the positioning of the stove, ventilation sources, heat-producing appliances, and the spatial distribution of various functions associated with cooking practices (e.g., food preparation, cooking, dishwashing etc) contribute to these differences. **Assessing vertical and horizontal temperature variability provides insights into localised heat exposure** (Luo et al., 2023; Rahman et al., 2014), which may disproportionately affect certain occupants based on their positioning in the cooking space. In addition, spatial characteristics like kitchen volume, ceiling height, number and placement of openings can be important for measuring indoor environmental conditions, including air supply and flow within the kitchen (Willers et al., 2006). In addition, since heat exposure and related stress are also impacted by indoor thermal comfort conditions, the specifications and operational details of any **Heating, Ventilating and Air-Conditioning (HVAC) systems** being used are also critical. **Effective ventilation can significantly reduce the accumulation of heat within the kitchen** (Willers et al., 2006; Zhang et al., 2021), while air conditioning can actively lower indoor temperatures (Liu et al., 2020). Monitoring the use and characteristics of these comfort-related technological systems combined with environmental and spatial factors helps to quantify their contribution to mitigating heat stress[1].

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[1] Within spatial characteristics of kitchens, it may also be important to consider other heat sources within the cooking environment, such as refrigeration equipment, lighting, and hot water use in dishwashers, and even the total number of occupants as humans also act as heat sources. While heat emissions from these sources may be less significant in domestic settings, they can be substantial and should be considered in commercial and institutional kitchens.

4.2. Cooking Technology Parameters

These relate to the characteristics and performance of cooking equipment and how these affect heat emissions and energy efficiency and are discussed in detail in section 0, along with the various evaluation methods used.

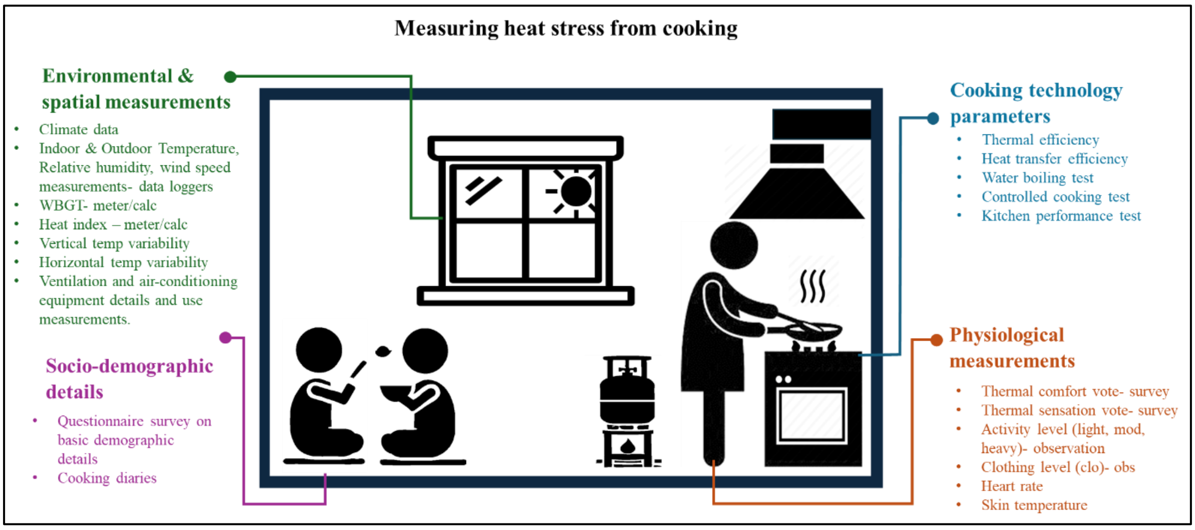


Figure 8: Various parameters involved in measuring heat stress from cooking (Source: Author)

4.3. Socio-demographic Measurements

Heat stress is also directly related to the social and demographic characteristics of the individuals involved, as discussed in section 3.2. **Relevant socio-demographic data including age, gender, and household characteristics, can be collected using questionnaire surveys, while cooking diaries can provide detailed accounts of cooking practices, frequency, and duration** (for example, see MECS' methodology and case-studies on cooking diaries from various countries). These social factors are crucial for understanding variations in heat exposure, as different cooking behaviours and routines can lead to significant differences in thermal experiences and energy consumption. Integrating socio-demographic data into heat stress assessments enables a more nuanced analysis that considers how factors such as cultural practices, economic status, and household responsibilities influence the risk of heat stress.

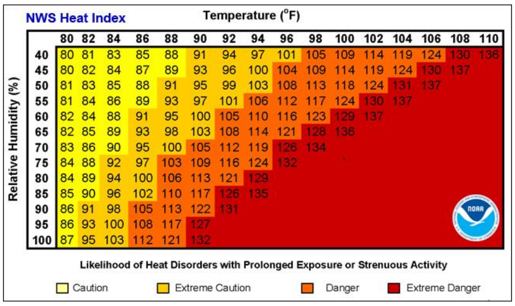
4.4. Physiological Measurements

Physiological measurements provide critical insights into how individuals respond to heat exposure, and their measurement involves a combination of **objective and subjective assessments**. Objective physiological data can include observations of **cooking activity level, clothing insulation (clo), and metabolic rate** of the cooks/kitchen workers. Previous studies related to cooking heat exposures have also measured **heart rate** (Anua et al., 2021; Frankowska et al., 2020) and **skin temperature** (Liu et al., 2020) as an indication of heightened thermal load on the body, and as a measure to quantify the body's physiological response to heat stress.

Measuring heat stress: Objective and subjective measures

Heat Index:

The heat index is a screening tool that uses temperature and relative humidity to calculate an adjusted temperature, representing how the conditions feel more accurately to the human body than just the ambient temperature (OTM, 2017). The HI can be calculated using a formula developed for the United States National Weather Services that is based on biometeorological studies that factor in various parameters, including vapour pressure, skin surface area, clothing, activity levels, wind speed, and the body's heat and moisture resistance. The model approximates the apparent temperature by considering the interaction between ambient temperature and relative humidity (Rothfusz, 1990).



NWS Heat Index

Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

🟨 Caution 🟨 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Figure 9: NWS Heat Index. Source: US National Weather Service (NOAA, 2016)

Wet-Bulb Globe Temperature (WBGT):

WBGT uses temperature, humidity, air movement, radiant heat, and other weather parameters in estimating heat stress. Since the WBGT uses four factors for calculating an adjusted temperature, it is considered as the most accurate tool when determining if there is a heat hazard present. WBGT is also considered more suitable for estimating outdoor heat exposure as it takes account of direct solar radiation. It is thus also used to inform activity modifications during exercise or outdoor work. WBGT measurements are most reliable when taken at, or as close as possible to, the work area, with environmental measurements taken at least hourly, during the hottest portion of each work shift, during the hottest months of the year, and when a heat wave occurs or is predicted (OTM, 2017). WGBT can be measured using WGBT meters that have three sensors that input data into a calculation that adjusts the temperature to represent the impact of humidity, wind, and radiant heat on heat strain:

$$\mathrm{WBGT}_{out} = 0.7\mathrm{T}_{nwb} + 0.2\mathrm{T}_{g} + 0.1\mathrm{T}_{db}$$

where,
T_{db} = the dry-bulb temperature
$\mathrm{T}_{\mathrm{nwb}}$ = the natural wet-bulb temperature
T_{g} = the globe temperature

Thermal sensation vote:

The Thermal Sensation Vote (TSV) is a subjective measure of how hot or cold a person feels at a given moment (ASHRAE, 2020). It specifically refers to the individual's direct sensation of thermal stimuli. It is typically measured using a seven-point scale which quantifies immediate thermal sensations based on how hot or cold an individual feels in their environment:

-3	-2	-1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

According to ASHRAE (2020), the range between -0.5 and +0.5 on the TSV scale is shown to represent the range where about 80% of occupants feel thermally satisfied and defines the acceptable comfort range for indoor environments.

(continued…)

Thermal comfort vote:

The Thermal Comfort Vote (TCV) is a broader assessment that reflects whether a person feels comfortable with their thermal environment, beyond just their immediate sensation of temperature (Chatonnet and Cabanac, 1965). It accounts for whether the person is content with the thermal conditions or if they would prefer a change (e.g., cooler, warmer) (ASHRAE, 2020). Different studies have employed different scales for thermal comfort, but most prevalent are a 4- or seven-point scale, derived from ASHRAE thermal sensitivity vote:

-3	-2	-1	0	+1	+2	+3
Very uncomfortable	Uncomfortable	Slightly uncomfortable	Neutral	Slightly comfortable	Comfortable	Very comfortable

While objective measurements offer a quantifiable assessment of the heat exposure potential, they do not capture the individual variability in heat perception and thermal comfort. Thus, **subjective assessments are essential for understanding personal comfort levels, as individuals may experience heat differently**. Subjective measurements such as the **Thermal Comfort Vote (TCV)** and **Thermal Sensation Vote (TSV)** are used to gauge occupants' perceptions of their thermal environment, offering an indication of whether they feel hot, cold, or neutral, and their level of satisfaction with the thermal environment (ASHRAE, 2020). These surveys account for personal differences in thermal tolerance, cultural expectations, and psychological factors that may influence how heat is perceived.

4.5. Heat loss and thermal performance of cooking technologies

The cooking process involves transferring energy from a fuel source to the food. As the temperature of the food rises, various chemical reactions occur, enabling cooking. This energy transfer can occur through different media, such as boiling water, hot oil, hot air, or microwaves, and relies on thermal conversion technologies (or stoves) to transfer energy from the fuel to the cooking vessel. However, **each stage of this process is inherently inefficient, leading to energy losses that can contribute to heat gains in the cooking environment.**

- **Fuel Conversion:** Poor combustion can prevent the full release of energy from certain fuels, such as animal dung. Additionally, excessive combustion airflow can divert energy toward heating unnecessary volumes of air, reducing efficiency.
- **Stove Heat Transfer:** Once energy is released from the fuel, it is transferred to the cooking vessel. However, inefficiencies at this stage are common. For instance, flames from an open fire licking the sides of a pot represent energy that escapes rather than being absorbed by the vessel. Similarly, stoves that generate more heat than the pot can absorb lead to further energy losses.
- **Vessel Losses:** Conservation of energy dictates that, once the pot reaches a stable temperature, the energy entering the pot equals the energy lost to the environment (minus the small amount absorbed by the food). Losses occur through heat dissipating from the pot's surfaces into the surrounding air or through water evaporation as steam. In an open flame scenario, heat may also transfer inefficiently from the flames to the pot.

Where cooking is done indoors, most of these losses will result in energy being released into the kitchen environment, resulting in heat gains. This excess heat raises the ambient temperature of the cooking environment, potentially exacerbating heat stress for individuals working in or near the kitchen.

The extent of heat loss from any cooking technology is determined by its thermal performance, which reflects how efficiently a cooking system transfers energy into the cooking vessel and food while minimising energy losses to the surrounding environment. Thermal performance is often measured as **thermal efficiency**—the ratio of useful energy delivered to the pot versus the total energy in the fuel. However, **beyond efficiency metrics, it is critical to consider how these inefficiencies contribute to heat dissipation into the kitchen.** This excess heat not only undermines energy efficiency but also heightens the risk of heat stress, particularly in already vulnerable or poorly ventilated indoor cooking spaces.

Heat loss in traditional solid-fuel cooking methods

Previous studies (Jetter et al., 2012; Smith, 1989; Smith et al., 1993; Venkataraman et al., 2010) show that in traditional solid-fuel cooking, two key factors influence heat loss (Figure 10):

- **Combustion efficiency:** this refers to how completely the fuel burns, or how much energy in the fuel is converted to heat. Incomplete combustion produces more smoke and particulate emissions.
- **Heat-transfer efficiency:** This indicates the efficiency of heat being transferred from the fire (products of combustion) to the pot. Inefficient heat transfer means more heat is lost to the surroundings instead of being used for cooking.

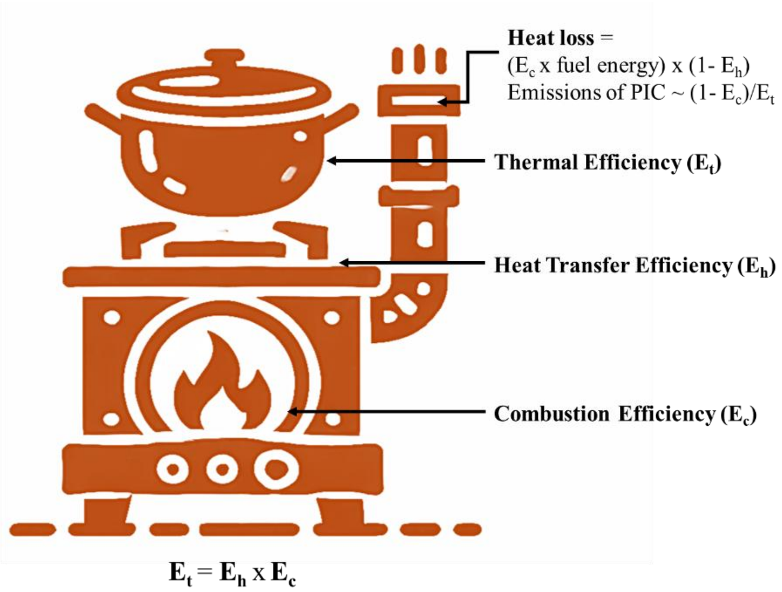


Figure 10: Stove efficiencies and their relationships (Source: Adapted from Venkataraman et al., 2010).

These efficiencies together form part of the overall thermal efficiency of a cooking technology. **Inefficiencies in combustion and heat transfer result in significant pollutant emissions and heat losses into the kitchen**, raising ambient temperatures and contributing to heat stress. However, Smith (1989) notes that combustion efficiencies and heat transfer efficiencies might not always work together, resulting in trade-offs between efficiency and emissions. For example, some improved biomass cookstoves aim to increase overall efficiency by enhancing heat transfer (e.g., enclosing the combustion chamber, reducing airflow). However, if this improvement leads to reduced combustion efficiency—e.g., due to restricted airflow—it can result in more emissions being released into the kitchen.

Thermal performance of cooking technologies – useful definitions

The overall thermal performance of any cooking technology and fuel use can greatly impact thermal comfort within the cooking environment and have implications for heat stress. Broadly, **thermal performance encompasses the overall thermal operation and effectiveness of a cooking system**. It is also influenced by aspects like **temperature control, fuel consumption rate, and emissions**. When a cooking technology has low thermal efficiency, a significant portion of the energy from the fuel is not used for cooking and is instead released into the surrounding environment as heat, leading to elevated indoor temperatures, causing thermal discomfort, and increasing the risk of heat stress.

In 2018, the International Organization for Standardization (ISO) developed a set of laboratory test protocols for evaluating cookstove performance (i.e. ISO 19867-1:2018) as a standard tool to establish international comparability in measurement of cookstove emissions and efficiency. The ISO Standard uses the terms cooking efficiency, thermal efficiency and energy efficiency interchangeably.

Overall Thermal Efficiency (OTE):

This refers to the overall efficiency of a cooking system in converting the energy stored in the fuel into useful energy into the pot. It is measured as the ratio of cooking energy delivered (i.e., energy into the pot) to fuel energy and is an indicator of stove energy efficiency.

The ISO (19867-1:2018) defines thermal efficiency as the ratio of *useful energy delivered* to *fuel energy used*. Here, the useful energy delivered is defined as the energy transferred to the contents of a cooking vessel, including sensible heat energy that raises the temperature of the contents of the cooking vessel and the latent heat of evaporation of water from the cooking vessel. The fuel energy used is defined as the product of the heating value of the raw fuel and its mass as fired, less the product of the heating value of the residual fuel, if applicable, and its mass:

$$\eta_c = \frac{\text{Useful energy delivered}}{\text{Total energy of fuel consumed}} \times 100$$

where:
Useful Energy Delivered = Sensible Heat Energy + Latent Heat of Evaporation

Fuel Energy Used = (heating value of raw fuel × mass of fuel fired) − (heating value of residual fuel × mass of residual fuel)

Similarly, the US Department of Energy (DOE) calculates cooking efficiency as the ratio of thermal energy absorbed by a metal block divided by the energy consumed by the device as it heats the block.

The American Society for Testing and Materials (ASTM) in its standard F1521 (applicable to both gas and electric ranges and cooktops), calculates cooking efficiency through a water boiling test as the change in thermal energy of the water divided by the energy consumption of the device. In all these standards, cooking efficiency is calculated as the amount of energy delivered to the pot divided by the total energy consumption by the appliance.

For combustion-based cooking, the Overall Thermal Efficiency is understood as a product of the Combustion Efficiency and Heat Transfer Efficiency (Jetter et al., 2012; Smith, 1989; Smith et al., 1993; Venkataraman et al., 2010):

$$\text{OTE} \sim \text{CE} \times \text{HTE}$$

(continued…)

Combustion Efficiency (CE):

Refers to the proportion of fuel energy converted to heat (Smith et al., 1993; Venkataraman et al., 2010). It is the measure of how completely the fuel is burned in the stove. High combustion efficiency indicates that most of the fuel's energy is released during the combustion process, producing minimal pollutants (e.g., carbon monoxide, particulate matter). Incomplete combustion reduces combustion efficiency and results in higher emissions and lower overall efficiency.

Previous studies note that emissions are a strong function of combustion efficiency, but only a weak function of thermal efficiency and heat-transfer efficiency. A 5% increase in combustion efficiency, from 90% to ~95%, for example, would decrease total emissions of products of incomplete combustion by about 50%, while increasing overall stove energy efficiency by only about 5% (Venkataraman et al., 2010).

Heat Transfer Efficiency (HTE):

This refers to the fraction of the heat released by combustion that is effectively used for cooking, representing the ratio between the heat delivered to the cooking pot and the total heat energy released during combustion (Jetter et al., 2012). It gauges how efficiently heat moves from the source (like a cookstove flame) to the cooking surface, rather than dissipating into the surrounding environment. This efficiency depends on factors such as stove design, pot placement, and airflow, with lower efficiency leading to greater heat loss to the surroundings.

Low heat transfer efficiency means more heat is wasted in the air, increasing ambient temperatures, especially in poorly ventilated spaces, which can heighten heat stress. This is particularly relevant for fossil-fuel-based stoves (e.g., wood, charcoal, kerosene), which release more heat than cleaner fuels like electricity. Consequently, stoves with low heat transfer efficiency contribute to greater heat buildup indoors, further compounding heat stress in inadequately ventilated or insulated homes.

Heat Loss in Gas Stoves

Gas stoves generally have higher combustion efficiency compared to solid-fuel stoves because gas burns more cleanly and completely. The controlled combustion process of gas result in lower levels of incomplete combustion products. However, they still contribute to heat loss in the kitchen due to inefficiencies in heat transfer. **Factors like burner design, flame control, air flow and pot placement affect how much heat is actually used for cooking versus how much escapes into the environment** (Smith, 1989). A further issue with gas is that it produces more water vapour per unit of fuel energy in the products of combustion, compared to charcoal and wood, increasing ambient humidity, and potentially affecting thermal comfort. The composition of the fuel also strongly affects burner performance, due to variations in occurrence of incomplete combustion (Ko and Lin, 2003). In addition, the variations in cooking pot size and composition, when combined with different burner sizes, further complicates the efficiency equation (Hager and Morawicki, 2013).

Reduced Heat Loss in Electric Cooking Technologies

Electric cooking technologies have shown to offer significant advantages in minimising heat loss. In electric cooking, **combustion efficiency is not relevant because there is no combustion process involved**. Combustion-less cooking improves the cooking process by eliminating emissions in the kitchen and combustion-related losses (such as incomplete fuel burning and energy lost in flue gases), thereby also improving cooking energy efficiency (Rasugu Ayub et al., 2021). Instead of burning fuel to generate heat, eCooking devices convert electrical energy directly into thermal energy or radiant energy (e.g. as microwaves) for cooking. In most electric cooking tests, thermal efficiency considers the ratio of useful energy delivered to the cooking vessel to the input energy from the source (Sweeney et al., 2014), whereas heat transfer efficiency focuses on the mechanisms by which heat is delivered to the pot (e.g., stove design, surface area, pot placement etc.). Standard metrics like the water boiling test do not directly isolate heat transfer efficiency as a separate metric but provide an indirect indication of it through the stove's design and operation during the test.

Electric Pressure Cookers (EPCs) and induction hobs generally exhibit high thermal efficiency due to efficient heat transfer mechanisms, whereas conventional electric coil technology typically has a comparatively lower thermal efficiency (around 74-83% (Sweeney et al., 2014)). Electric coil cookstoves use resistance heating elements (the coils) that heat up when electric current passes through them. Heat is then transferred from the coils to the cookware primarily through conduction. As such, some heat is lost to the surrounding air due to the exposed heating elements. The transfer of heat from the coil to the cookware is comparatively less efficient because it relies on direct contact, and not all the heat generated reaches the food. This means that **in electric coil cookstoves, heating efficiency can differ based on the diameter of the cooking vessel**, which if large enough to completely cover the coil elements can improve efficiency (US DOE, 2014).

Induction cooking works by using magnetic induction to generate heat directly within the cookware. When a ferromagnetic pot is placed on an induction hob, an oscillating magnetic field creates eddy currents in the metal. These currents then produce heat through the Joule effect, effectively heating the pot itself rather than the cooktop surface, which **enhances efficiency and control in cooking** (Sweeney et al., 2014). As such, less heat is lost in poor thermal conduction between heating element and cookware (Figure 11). Efficiency of inductive cooking systems is found to be about 90% (Sadhu et al., 2010), and are shown to transmit heat to the food/cookware faster than gas, cutting down on cooking times (Rasugu Ayub et al., 2021; Sadhu et al., 2010). **Reduced cooking time also lowers the potential for heat transfer to the surrounding environment**. Other energy efficiency improvement techniques in cooking that also result in reducing heat emissions include insulation, containment of escaping steam while cooking and automating the cooking vessel with micro-controllers (Rasugu Ayub et al., 2021), and are found in EPCs, which generally makes them the most efficient cooking technology, drastically reducing heat loss. Automated devices also allow the cooking of food without supervision or even the presence of the cook within the kitchen space, further mitigating heat exposure. **A study by MECS indicates that modern hobs (induction and infrared) can reduce energy consumption by about 10% compared to resistive element hotplates, with automated devices like rice cookers achieving approximately 25% savings, while EPCs can save up to 50%** (Scott and Leach, 2023). Additionally, tests on larger EPCs with capacities of 33, 40, and 65 litres (Batchelor, 2021) demonstrate efficiency and cost per meal comparable to those of domestic EPCs.

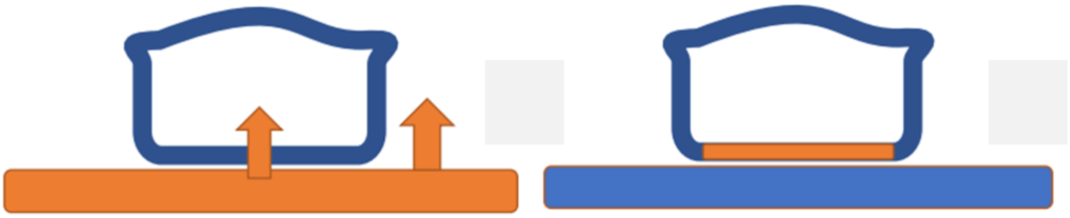


Figure 11: Hot resistive element passing heat to the pot and escaping up the sides of the pot (left); induction generates heat in the bottom of the pot only (right) (Credit: Dr Simon Batchelor).

Methods for determining cookstove efficiency

Cookstove efficiency is crucial for evaluating the energy use, emissions, and overall environmental and health impacts from cooking. Several methods and metrics are employed to assess cookstove efficiency, focusing on how effectively they convert fuel into usable heat for cooking. This is useful to understand heat loss and consequent heat stress related to cooking practices. Although the Controlled Cooking Test and Kitchen Performance Test are not direct measures of cookstove efficiency, however, they provide useful means of comparing the energy consumed when cooking with different fuel/stove combinations.

Water Boiling Test (WBT):

This is a laboratory-based method that evaluates the cookstove's *thermal efficiency* by measuring the time and fuel required to boil a specified amount of water and keep it simmering. It involves heating a pot of water until boiling and then maintaining a simmer (for a fixed time, usually 30-45 minutes), tracking the fuel used, and monitoring temperature changes. In this way, it can calculate thermal efficiency (percentage of energy transferred to the water), fuel consumption, and emissions.

The WBT doesn't fully represent real-world cooking conditions, but it provides a baseline comparison of stove performance.

Block Tests:

This is a laboratory-based method that uses either aluminum and anodized aluminum blocks for gas stoves and ovens, respectively or a carbon steel block which is used as an alternative to the aluminum block test in the evaluation of induction stoves (Hager and Morawicki, 2013). The test procedure typically involves heating a standardised aluminum or steel block that is fitted with a thermocouple (for internal temperature monitoring) to determine how efficiently the stove converts fuel into usable heat by measuring the amount of fuel consumed, the temperature change in the block, and the energy released from the fuel.

Block and brick tests are standardised and reproducible, but reporting the thermal efficiency for metal blocks is dissimilar to heating food products; thus, arguably, the use of the water boiling test is a more accurate depiction of practical efficiency for consumers.

Controlled Cooking Test (CCT):

The CCT is a field-based test that can be used to compare energy consumption from different cookstoves under more realistic cooking conditions than the WBT by having local cooks prepare a standardised meal. Data on fuel use, emissions, and cooking performance is collected from actual cooking scenarios by tracking the fuel consumed, cooking time, and other variables like thermal performance and heat transfer efficiency. As such, it provides a better sense of user interaction and variability.

Though more representative than WBT, variations in user habits and local foods can still affect consistency.

Kitchen Performance Test (KPT):

The KPT is a field-based method designed to yield insights into stove efficiency, fuel consumption, and emissions under real-world usage conditions over a longer period. It involves monitoring households over several days as they use the cookstoves for their regular cooking tasks. Fuel consumption is measured before and after the testing period- usually a baseline measurement followed by a transition phase. It provides insights into daily fuel consumption, stove efficiency, overall thermal performance and user behaviour in actual cooking environments.

Results can vary significantly due to user habits, but this test is highly reflective of real-world use.

(continued…)

Energy ratio:

An energy ratio approach based on real-world cooking practices (e.g., CCTs) was proposed by Scott et al. (2024) to overcome the limitations of WBT in measuring efficiency of electric cooking appliances like EPCs and rice cookers. Energy ratios can be calculated by comparing the performance of any two fuel/stove combinations. For example, it can be used to calculate the amount of energy consumed by a traditional fuel stove versus the energy used by a modern electric appliance (like EPCs) to cook the same dish. This metric accounts for not just thermal efficiency, but also factors like insulation, automation, and pressure cooking which are inherent in modern appliances. An important feature of energy ratios is that they can be calculated from field measurements of energy consumption by households, so they represent real life conditions (similar to KPT) and also reflect user behaviour.

Energy ratio calculations are based on real-world cooking practices unlike the WBT, which standardises the cooking process (e.g., simmering for a fixed duration), and thus can capture variations in user behaviour, cooking styles, and dish types. This approach thus inherently captures the heat output from different cooking devices, which directly contributes to indoor temperatures.

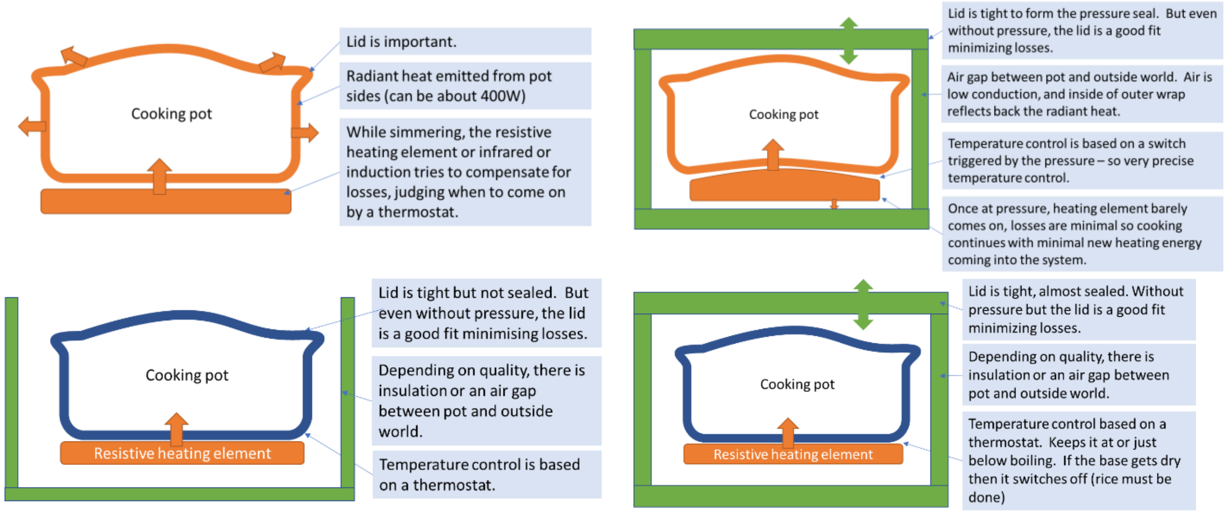


Figure 12: Heat loss in induction, resistive hotplates and infra-red stoves (top-left), Electric Pressure cookers (top-right, slow cookers (bottom-left) and rice cookers (bottom-right) (Credit: Dr Simon Batchelor).

Limitations of thermal efficiency

It is also important to note that there are limitations to calculations of thermal efficiency. Whilst various studies have provided efficiency ranges for different fuel cookstoves (Barpatra Gohain and Dutta, 2024; Jetter et al., 2012; Makmool et al., 2007; Mekonnen, 2022; Shen et al., 2018; Slavova and Marinova, 2017; US DOE, 2014), there is broad consensus that **efficiency values can vary significantly based on differences in specific burner/cookstove design as well as cooking performances and behaviours**, all of which greatly impact thermal performance and the dynamic properties of heat flow. Furthermore, standard testing measures calculate thermal efficiency as energy efficiency, understood in terms of useful energy into the cooking vessel. However, this is different from the *actual energy that is needed to cook food*- a distinction highlighted by MECs research. As explained by Scott et al. (2024), contemporary cooking appliances like EPCs offer unique cooking functions, combining **pressurisation, automation, and insulation** to cook food at higher pressures and temperatures. This process not only reduces cooking time but also consumes less energy. Given these specialised features, **it is less meaningful to compare efficiencies across cooking devices, as they provide different types of cooking services and performance characteristics.** Moreover, it is worth noting that with electrical appliances like rice cookers, slow cookers and EPCs, the level of heat exposure for the end-user is not only reduced significantly from their insulating characteristics, but also from the fact that they do not require monitoring and continued presence within the cooking space, greatly alleviating heat burdens for end-users while also offering added benefits of time savings. Nevertheless, to understand heat emissions from eCooking, **the heat transfer efficiency of an electrical appliance can still be an important measure to determine how much heat loss occurs**, which results in increasing ambient temperatures and consequently, contributing to heat stress.

Cooking heat loss- a socio-technical phenomenon

Heat loss from a cooking technology depends not only on the fuel type and the cookstove design, but also the cooking methods and user practices. The behaviour of the cook can greatly impact real-world cooking experiences, which then influences energy consumption as well as heat dissipation (Hager and Morawicki, 2013). As Hager and Morawicki (2013) summarise in their review of cooking behaviours, practices like carefully controlling the stove's heat can reduce energy use compared to hurried cooking at maximum stove power, potentially cutting energy consumption in half. **Adjusting the heat to achieve a simmer instead of a full boil can save over 70% of energy**, while using a lid on the pot minimises heat losses due to evaporation. Additionally, filling the pot to capacity improves efficiency, as a pot filled to only 20% capacity consumes twice as much energy as a full one. Practices like passive cooking—where a dish is partially cooked and then allowed to finish as it cools—also help conserve energy. The use of non-powered thermal cookers, such as wonderbags, is also quite popular in certain regions for slow cooking processes. Using flat, undamaged pots can save over 40% in energy, and soaking dried foods like beans before cooking can reduce energy use by up to 20%. These behaviours collectively demonstrate how adjustments in cooking practices can significantly impact energy consumption as well as reducing overall heat stress. **Thermal variations resulting from differences in cooking behaviours are often much greater than the differences in performance between different modern fuel devices.** As a result of these variations, Smith (1989) and Scott et al. (2024) propose moving beyond understandings of 'efficiency' which implies a degree of universality that is rarely achievable, towards understanding of performance based on relative rankings to provide a better estimate of energy consumption as well as heat losses.

To summarise, different fuels (like wood, charcoal, gas and electricity) have different characteristics, which combined with the cookstove design and cooking behaviour, can greatly impact the amount of heat transferred to the cooking utensil (Makmool et al., 2007) versus heat loss to the environment that contributes to heat stress. Overall, **electric cooking technologies, due to their higher thermal efficiencies, effective heat transfer mechanisms and reduced cooking times, substantially reduce heat losses into the kitchen environment** compared to traditional cooking methods. And in the case of rice cookers, slow cookers and EPCs, heat stress is further reduced due to a reduction in end-users' exposure to heat. By minimising excess heat dissipation and eliminating combustion-related heat losses, these technologies help lower ambient temperatures in the cooking space. Consequently, adopting electric cooking devices can significantly reduce heat stress for individuals involved in cooking activities, improving thermal comfort and overall health outcomes.

5. Linking health and heat impacts in cooking

Cooking activities, particularly those that involve high temperatures, have been linked to significant health and environmental impacts due to heat emissions and air pollutants. In addition to the direct health impacts resulting from extreme heat and thermal strain, as highlighted in Section 2, the type of cooking method, the fuel used, and the duration and intensity of cooking all influence the amount of particulate matter (PM), volatile organic compounds (VOCs), and other emissions released into indoor environments, which in turn can affect human health and heat stress levels.

The temperature and duration of cooking significantly impact emission rates, as shown by Lachowicz et al. (2022). Whilst the use of biomass fuel is associated with elevated PM concentrations, the study further shows that different cooking methods like boiling, steaming, smoking, frying, and grilling not only influence PM concentration, but also chemical composition and morphology. **Cooking techniques that require prolonged heat and higher temperatures, such as grilling, result in higher emissions of PM and polycyclic aromatic hydrocarbons (PAHs)**, especially when using biomass fuels like wood, which can emit up to five times more PAHs compared to charcoal or clean fuels like LPG. **Frying, especially at high temperatures, has been found to release substantial amounts of fine particulate matter**, contributing to poor indoor air quality. At high temperatures, deep frying can release not just particulate matter but also volatile organic compounds (VOCs), both of which contribute to poor indoor air quality. Boiling and steaming involve lower temperatures, resulting in fewer particulates. In their study of GHG emissions from various cooking methods and foods, Frankowska et al. (2020) show that **cooking emissions can be at least halved (in the case of toast) and reduced up to 16-fold (in the case of tofu/Quorn) by changing the cooking method used**. Additionally, the composition of the food being cooked, and the ingredients being used, influence emissions; meat, for example, produces more PAHs than vegetables during grilling. The study further found that overall PM concentration related to cooking activities is higher during the winter, since natural ventilation is limited, e.g., from keeping windows and doors closed, further exacerbating indoor air quality issues (Lachowicz et al., 2022).

Some studies also indicate that **the links between heat and pollutant emissions can be complex**. For example, Smith (1989) found that there can be trade-offs between efficiency and emissions in many traditional fossil-fuel/ICS stove designs. Increasing heat transfer efficiency by modifying the stove design (e.g., enclosing the combustion chamber, reducing airflow) can sometimes reduce combustion efficiency because it may lower the air-to-fuel ratio, leading to incomplete combustion. As a result, while the overall thermal efficiency might increase, the emissions could also rise due to lower combustion efficiency. Similarly, Venkataraman et al. (2010) highlight that while carbon monoxide (CO) emissions generally decrease with higher combustion temperatures, PM emissions are more complex, influenced by factors such as air mixing and combustion dynamics. Hydrocarbons generated during combustion can condense to form organic carbon particles, particularly in low-temperature flame regions. The study indicates that CO and PM emissions do not follow a straightforward relationship with high temperatures and heat, underscoring the need for addressing each pollutant separately.

Indoor environmental conditions, such as temperature and relative humidity (RH), both play a significant role in the distribution and response of cooking-related emissions. Kumar et al. (2022) observed a week correlation between CO_2 levels with RH and temperature, which the authors suggest can be attributed to the low water solubility and inherent greenhouse potential of CO_2, respectively. They also found that RH remains relatively unaffected by the type of fuel used but is more sensitive to factors like ventilation and kitchen volume. Zhao et al. (2014) demonstrate a similar relationship between COx, temperature and RH values. Using experimental data and environmental monitoring during cooking various Chinese cuisines in a residential kitchen, they showed that **COx concentrations are somewhat related to temperature, but not to RH, and are strongly influenced by the type of cooking process undertaken**, such as burning of high-purity liquor, frying or stewing, and most significantly, with the burning of fuels such as gas. The Total Volatile Organic Compounds were linked more strongly with the use of seasonings and ingredients, and less with the cooking time and technique. Further, their study showed increases in indoor temperatures by 4.0 to 11.5°C and RH levels by 15% to 30% with different cooking styles in their residential kitchen setting. Mechanical ventilation, while somewhat effective in reducing heat, was insufficient to lower RH to comfortable levels, indicating a persistent challenge in managing heat stress and air quality in kitchen environments.

Cooking with different fuels also impacts emission profiles. Buonanno et al. (2009) revealed that emissions vary significantly depending on the type of fuel, cooking method, and the type of food being prepared. For example, gas stoves tend to produce higher particle emissions compared to electric stoves, especially during high-heat cooking processes like grilling and frying. This is attributed to direct emissions from the combustion of gas. As with other studies, their research also highlighted **that cooking fatty foods generates more particulate emissions than vegetables, with emissions heavily influenced by the type of oil used and the surface temperature of the food**. Their study also demonstrates the links between cooking temperatures and particulate matter emissions, showing that particle number, surface area and mass concentration all increased for higher temperatures, for both gas and electric stoves.

Ierardi and Pavilonis (Ierardi and Pavilonis, 2020) noted that in school kitchens, while temperatures increased over the day, RH levels tended to decrease. The interaction between heat and humidity, however, further complicates the indoor air environment. While higher temperatures during cooking are generally associated with higher PM levels due to increased emissions from combustion and thermal cooking processes, RH also plays a critical role in the accumulation and behaviour of PM indoors. Some studies (Vaishali et al., 2023) have shown that RH modulates the relationship between temperature and PM concentrations in outdoor environments[2], while others (Tanatachalert and Jumlongkul, 2023) suggest a positive relationship between RH and PM2.5 concentrations in open atmospheric environments. **High humidity can contribute to the hygroscopic growth of particles, where PM absorbs moisture, increasing in size and prolonging residence time in the air**. In humid kitchen environments, this effect can amplify indoor PM levels by facilitating particle growth and altering their dispersion. These findings indicate that **the interplay between temperature, humidity, and PM behaviour is complex and varies depending on the specific conditions of the cooking environment**.

As Smith (1989) observes, predicting the health impacts of changes in cooking heat transfer, combustion, and overall efficiencies is complex. While emissions themselves do not directly contribute to heat, the literature in this section suggests that heat exposure can be linked with emission factors. Heat exposure is also influenced by the rate of emissions, cooking duration, ventilation, proximity to the stove, and other environmental and behavioural factors, some of which may be affected by stove modifications aimed at improving cooking thermal efficiency. Consequently, **laboratory and simulated tests offer only limited insights into real-world exposures**, underscoring the need for field tests to accurately assess the links between health and heat implications of improved cookstove technologies.

6. Urban cooking and heat stress: a literature review

Heat stress in urban environments has been the focus of much previous research, however, less attention has been given to the contributions of cooking to urban heat. This section provides an overview of the existing literature that links heat stress and cooking in urban environments, focusing on domestic and institutional settings.

6.1. Mapping thermal comfort and cooking heat in domestic settings

Although the reliance on clean cooking solutions has been growing in urban areas in recent years, as of 2022, about 12% of the population still lacks access to clean cooking, according to WHO Household Energy Database. In 2022, in low- and middle-income countries (LMICs), gaseous fuels (liquefied

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[2] According to Vaishali et al. (2023), at high RH (>50%), a strong negative correlation exists between temperature and PM2.5. Higher RH absorbs more solar radiation, reducing ground-level temperatures, weakening atmospheric dispersion, and increasing PM2.5 concentrations. At low RH (<50%), the relationship between temperature and PM2.5 is weaker, since lower humidity conditions allow for more effective solar radiation and atmospheric mixing, which helps disperse PM2.5.

petroleum gas [LPG], natural gas, biogas) were used by 60% of people (4 billion) as their main energy source for cooking, while unprocessed biomass (wood, crop waste, dung) was the main fuel for 26% of the population (IEA, IRENA, UNSD, World Bank, WHO, 2024). Cooking activities generate and retain heat, especially in confined indoor environments, resulting in elevated temperatures and humidity levels that impact thermal comfort (J. Li et al., 2024), and increase the risk of heat-related health issues. Research shows that traditional biomass and solid-fuel cooking is still prevalent in many low-income and informal urban contexts across the global South (Akintan et al., 2018; Butera et al., 2016; Kitole et al., 2023). This continued use of dirty cooking fuels is aggravated by rapid urbanisation and rural to urban migration that is not coupled with corresponding socio-economic enablers for urban dwelling (Okore et al., 2022). Further, even with access to clean solutions, **fuel stacking is still common, even in urban areas** (Chaudhary et al., 2022; ESMAP, 2020), which can significantly contribute to health and heat impacts. **Traditional cooking methods, fuel choices, and confined cooking environments become key contributors to heat stress in densely populated urban areas.**

Urban households' choice of cooking fuel is often associated with household size, sources of household income, education level, living conditions, as well as the accessibility and affordability of energy (Kitole et al., 2023; Pangaribowo and Iskandar, 2023; Zhu et al., 2022). Investigating women's food choices in informal settlements in Nairobi, Downs et al. (2022) found that limited access to cooking fuel and physical cooking space influenced dietary practices. **Women reported preparing fewer meals that required longer cooking times or greater fuel use, with the lack of adequate cooking space further restricting their ability to prepare such meals.** This often resulted in less nutritious meals, and an increased reliance on food vendors. Similar patterns were observed in Kampala, where Mguni et al. (2020) found that poverty constrained households to avoid energy-intensive cooking practices to conserve fuel. Such cooking fuel and food choices are critical to understand the implications for heat stress. Increased household income tends to inspire diversification of fuels used with addition of more cleaner options (Okore et al., 2022) that can potentially reduce heat stress. Li et al.'s (2024) study of Chinese households revealed that on average, households devote approximately 3.6 hours daily to residential kitchens, making cooking a significant daily activity; however, the study found that **89% of respondents reported dissatisfaction with their kitchen environment, highlighting a substantial gap in comfort and usability.** Their study revealed that urban kitchens are often small and poorly ventilated, allowing heat from cooking to accumulate. **This thermal build-up not only raises temperatures but also requires additional energy consumption for ventilation or cooling, further burdening low-income households.** Moreover, domestic cooking— predominantly carried out by women in many regions—frequently occurs without any health and safety measures, leaving domestic kitchen workers exposed to high levels of heat stress.

Rahman et al. (2014) show through simulated models that cooking can raise residential kitchen ambient air temperatures significantly, even with exhaust systems in place, with high-temperature zones persisting in areas near the cook. **With an initial ambient temp of 27°C, gas cooking led to heat accumulations in the upper portions of the room, ranging from 41-54°C**, with and without mechanical ventilation, respectively. Such studies demonstrate the severe thermal conditions possible in urban settings without adequate comfort and cooling solutions.

High indoor temperatures and poor ventilation contribute to thermal discomfort, especially when combined with the asymmetric heat exposure that occurs in kitchens (Zhang et al., 2021). For instance, Luo et al. (2023) observed that cooking activities create vertical and horizontal temperature differences, resulting in uneven heat exposure that can cause localised thermal discomfort. Previous studies have documented **significant vertical temperature differences in domestic kitchens, with findings showing variations exceeding 6°C** (Wei et al., 2017), **reaching up to 7°C** (Luo et al., 2023), **and peaking at 8.6°C** (Simone et al., 2013). Further, according to Simone et al. (2013), daily temperature variations in kitchens— observed in over 100 kitchens across the United States— were up to **10 °C** in cooking areas. Thermal radiation from the hot appliances raised the operative temperature by an additional **5.8°C**. Liu et al. (2020) demonstrate that gas stoves, which are common in urban areas, expose cooks to intense heat, particularly on body parts closest to the heat source, with **skin temperatures rising by 3.4°C at these areas**, while less exposed areas experienced minimal temperature increases. This pattern of localised heat exposure can lead to thermal strain and increased heat stress for cooks and kitchen workers.

Indoor temperature and humidity levels during cooking periods create an environment conducive to heat stress, especially in kitchens using biomass or kerosene stoves. Giwa et al. (2022) conducted a study on air quality, noise, thermal comfort, and health risk assessment of urban household kitchens in Nigeria where kerosene stoves are prevalent, and found that relative humidity (RH) levels averaged around 68% during cooking, with temperatures reaching nearly 30°C. Such high RH and temperature levels increase the heat index, indicating conditions suitable for heat-related health risks like heat exhaustion, heat stroke and heat cramps. Kumar et al. (2022), in an extensive study spanning low-income kitchens across 12 cities, found that **87% of kitchens exceeded the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) thermal comfort standards (i.e. RH >40%, temperature >23 ◦C) during cooking**, with temperatures often reaching 28 ± 2°C. They also found that **43% of kitchens violated the conditions for ideal ventilation**. Their study reveals that on average, people spend 2-3 hours daily in kitchens, with weekly cooking durations ranging from 5.1 to 22 hours. They also show that **RH levels ranged widely depending on ventilation and cooking type.** High RH levels (60–80%) were found mostly in African households (Figure 14) due to lack of mechanical ventilation, small volume kitchens, and cooking type. In terms of cooking fuels, the lowest average RH (44 ± 8%) was found in kitchens using a combination of electric and charcoal, while kitchens using LPG exhibited the highest RH levels (82 ± 4%). However, the variations in the RH were similar among other fuel types, indicating that fuel types do not influence in-kitchen RH significantly. Examining in-kitchen temperature ranges grouped by fuel type, they found that combinations of charcoal + natural gas, and kerosene + electric showed the highest and lowest temperature values of 29 ± 2 and 25 ± 3°C, respectively (Figure 13). During cooking, the **highest RH average was found for the surveyed African countries (58–81%), followed by Asian countries (62–72%), and the highest temperature average (24–33 ◦C) was found for Asian countries** in the study (Figure 14).

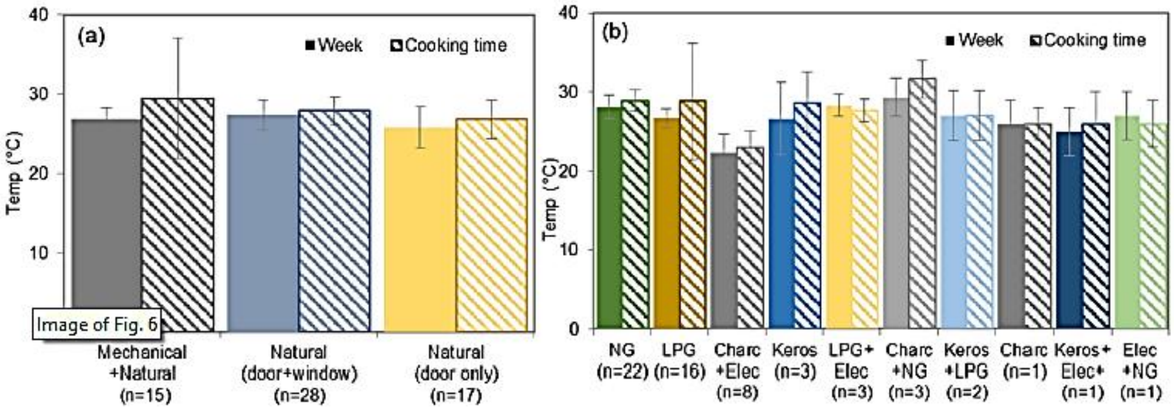

Figure 13: The weekly and cooking session averaged temperature (°C) across different kitchen ventilation conditions (*left*) and cooking fuel types (*right*) (Source: Kumar et al., 2022).

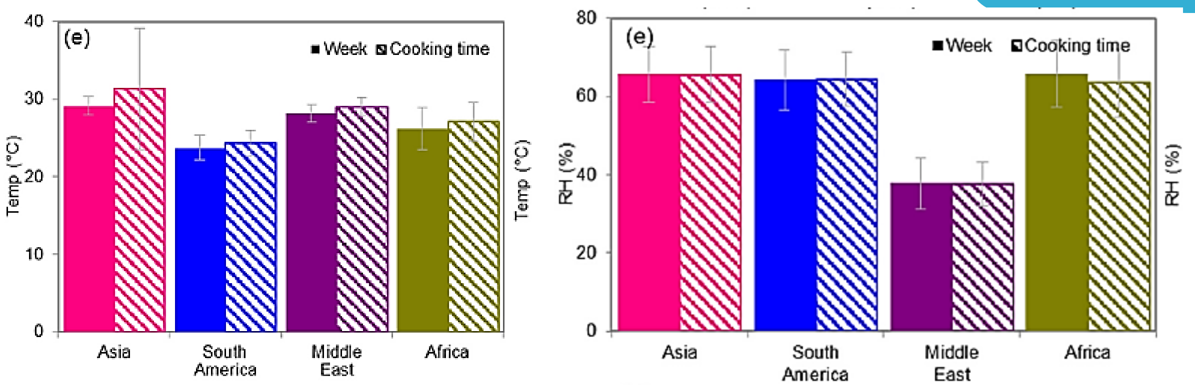

Figure 14: The weekly and cooking session averaged temperature (°C) (*left*) and RH (*right*) across different regions (Source: Kumar et al., 2022)

Similar results have been found by MECS' own studies (Scott et al., 2024) which show that African dishes tend to be more energy-intensive than Asian dishes, although Asian cooking (e.g., in Myanmar and Bangladesh) was found to generally employ a much greater variety of cooking devices. These and other studies (Willers et al., 2006) also indicate no significant correlation between RH and fuel type. Instead, higher RH levels are more commonly associated with cooking type, such as boiling and steaming, whereas frying tends to result in elevated temperatures. This pattern may explain the **variations in temperature and humidity observed across kitchens in different regions, reflecting regional preferences or dominant cooking methods.** This implies differences in impacts of heat exposure and related stress in different regions, countries, and even specific contexts (such as slum or informal urban settlements etc). Such findings also inform the design of clean cooking interventions, suggesting that region-specific strategies could be more effective in reducing heat stress and enhancing thermal comfort in kitchens. Additionally, Kumar et al.'s (2022) study highlights that **kitchens with larger surface areas or higher ceilings can significantly mitigate heat stress**. The study also emphasises that **improved ventilation— preferably a combination of natural and mechanical systems—plays a crucial role in reducing heat-related discomfort**. These recommendations can be extended to the types of fuels and cooking technologies used to mitigate active heat gains into the environment.

Figure 15: Cooking with gas in single-room occupancy in densely populated low-income urban areas in Pakistan. Source: Author

The health impacts of cooking heat stress in urban kitchens are severe, particularly in informal settlements where overcrowding, lack of green spaces, and poor building materials exacerbate the effects. Residents in informal settlements experience higher heat exposures than those in formal housing, as noted by Adegun (2024), which increases vulnerability to heat stress and related illnesses. Studies show that **informal housing areas experience higher surface temperatures and urban heat island effects compared to formal housing areas**, amplifying ambient heat exposures (Mehrotra et al., 2018). Here, spatial characteristics of dwellings and neighbourhoods become even more critical in relation to heat exposure, since informal housing is often of an inadequate standard when it comes to thermal comfort (Figure 15). Moreover, during hot weather or heatwaves, **cooking outdoors— a common practice due to limited indoor kitchen space— presents multiple challenges, such as insufficient or unsafe spaces** (Adegun, 2024; Kansiime et al., 2022), **increased exposure to direct sunlight** (McKinsey Sustainability, 2021), **and greater vulnerability to heat stress** (Laue et al., 2022). Mguni et al. (2020) found that residents in informal settlements in Uganda often cook outdoors, which, while avoiding indoor smoke, subjects them to compounded heat from the cooking process and ambient conditions, posing risks of heat exhaustion and heat stroke. **Higher burns and heat-related injuries have also been evidenced in informal settlements** (Zerbo et al., 2020). Similarly, Kansiime et al. (2022) found an increase in particular matter (PM2.5) concentrations in outdoor cooking areas in Ugandan informal settlements, although it showed lower CO concentration. In densely populated informal settlements, numerous households cooking outdoors simultaneously can contribute to localised increases in ambient temperature and air pollution from toxic smoke and particulate matter of cooking and heating (Zerbo et al., 2020), further contributing to the UHI effect and intensifying heat stress for the entire community.

Fuel-stacking for cooking is especially prevalent in urban informal settlements, although whole fuel composite data is often lacking (Okore et al., 2022). This continued reliance on unclean cooking fuels is further compounded by housing insecurities, poverty and infrastructural limitations (Boateng and Adams, 2022). For instance, Patel et al.'s (2020) multi-factor approach to determining slum severity in India revealed that access to kitchen spaces and clean cooking fuel was the leading type of housing deprivation for one-third of urban residents in India. **The use of unclean cooking fuels together with inadequate kitchen spaces exacerbates the adverse health and heat impacts to which residents of urban informal settlements are exposed.** Mguni et al. (2020) note that slum and informal settlement residents often lack access to cleaner fuels due to their legal status and the absence of government support, reinforcing dependence on traditional biomass fuels. Land tenure insecurity and diminished right to the city can further constrain residents' agency to mitigate heat stress.

In many cases, **cooking and heating needs are interwoven, with residents using the same unclean fuels for both**, especially in colder months (Kovacic et al., 2019). For instance, studies from African informal settlements show a preference for fuels like charcoal and kerosene, which serve both cooking and heating functions (whereas gas and electric cookers are not generally used for heating), indicating that separating cooking and heating fuels could be challenging in contexts where fuel versatility is critical (Okore et al., 2022). This dual usage of cookstoves for heating during winter may contribute to improved winter thermal comfort but also exacerbates health risks due to prolonged exposure to emissions and can result in increased heat stress in summer months. Nevertheless, some previous studies (Burguillo et al., 2022) also show that households experiencing energy poverty are more likely to rely on unclean fuels for cooking than for heating.

6.2. Cooking heat beyond the house: Institutional and commercial settings

Cooking heat stress is not confined to domestic kitchens; it extends to institutional and commercial settings, where cooking is performed at larger scales and often in high-density environments. These settings, including schools, hospitals, prisons, community centres, restaurants, and street food vendors, can contribute significantly to urban heat stress. As part of the formal economy, such spaces are subject to occupational health and safety (OHS) standards, making the documentation and mitigation of heat stress both viable and critical. Moreover, the hospitality industry and food service sector are growing rapidly, with institutional and commercial kitchens forming a substantial component of urban cooking and, consequently, urban heat generation.

Whilst most studies on domestic kitchens primarily focus on spatial characteristics and ventilation design to address the negative impacts of indoor air pollution from the use of dirty cooking fuels, the impacts of heat exposure from cooking have been explored more extensively in the context of commercial and institutional kitchens, often emphasising the experiences and health risks faced by kitchen workers. Institutions such as schools, hospitals, prisons, and community centres often operate kitchens to cater to large groups of individuals, amplifying the heat load due to the volume of cooking required. For example, in New York City public schools, Ierardi and Pavilonis (2020) found that **80% of kitchens exceeded heat exposure thresholds for heavy work scenarios**. In such settings, heat exposure is exacerbated by the extended operating hours and limited ventilation infrastructure, often leading to suboptimal thermal conditions for workers. Nsengiyaremye and Khalifa's (2023) study on institutional cooking in Lesotho similarly found that the use of LPG and firewood created school environments that were thermally uncomfortable, unhealthy, and heavily polluted (Figure *16*).

Additionally, the physical effort involved in cooking is influenced not only by the quantity and method of cooking but also by the technology employed. For example, biomass stoves demand considerable labour for fuelwood collection and preparation, as well as continuous presence (noted earlier). On the other hand, **modern appliances like rice cookers and electric pressure cookers (EPCs) significantly reduce workload by lowering physical exertion, thus indirectly alleviating heat stress** and enhancing thermal comfort for cooks. As such, these technologies demonstrate the co-benefits of transitioning to cleaner cooking solutions.

Figure 16: Outdoor cooking with firewood for school meals. (Source: *(Nsengiyaremye and Khalifa, 2023)*

Figure 17: Outdoor multi-fuel cooking for small businesses. (Source: CREEC. Uganda, 2022)

A 2024 baseline survey by the World Food Programme (WFP, 2024) of five schools under Sri Lanka's National School Meals Programme (NSMP) highlights similar thermal challenges in institutional cooking. As part of the Clean Energy Integration for School Meal Program (Solar Project), the survey revealed that all five schools used firewood as their sole cooking fuel. The heavy reliance on firewood contributed to high indoor temperatures, particularly in three schools with enclosed kitchens, two of which lacked proper ventilation. The excessive heat gains from cooking in these kitchens necessitated their separation from other school facilities. However, this separation created logistical challenges, particularly for meal transportation, which further strained the program's efficiency. **Poor kitchen design and ventilation also negatively impacted children's health in some schools**, causing coughing and breathing difficulties. Only one school reported a kitchen layout that was adequately suited for meal preparation.

Similarly, kitchens in hospitals and prisons, which operate continuously, can face compounded heat stress issues due to the scale and frequency of cooking activities. In high-density urban areas, restaurants and street food vendors can become critical contributors to urban heat stress. Restaurants, particularly those with open kitchens, generate substantial heat due to the high-powered cooking equipment used, such as gas stoves, ovens, and charcoal grills. **Street food vendors, often operating outdoors with minimal shade or cooling, are exposed to dual heat sources: the heat from cooking and ambient environmental heat**, making them especially vulnerable to heat stress. The MECS programme has highlighted the challenges faced by street food vendors, particularly in low- and middle-income countries, where cooking is often done using biomass or charcoal stoves (Figure 18, MECS, 2022). These inefficient cooking methods not only produce excessive heat but also lead to increased exposure to harmful pollutants. Additionally, vendors often operate in informal setups with limited access to cooling infrastructure, exacerbating their heat exposure and health risks. Moreover, Jiang et al. (2024) signify the importance of understanding heat risks for food delivery riders who often work intensively during severely hot midday hours with minimal rest time, and so are particularly vulnerable to heat stress.

Figure 18: Solid fuel cooking by street food venders in Cambodia. (Source: (MECS, 2022)

Institutional and commercial kitchens typically involve large-scale meal preparation, significantly increasing heat output. **Cooking processes contribute to the majority of heat gains in commercial kitchens, which when combined with radiant heat from appliances and limited ventilation, often necessitates cooling systems to maintain a tolerable working environment**. For instance, Singh et al. (2022) measured environmental parameters and indoor air quality in a commercial kitchen in India, finding elevated temperatures and humidity levels due to cooking, which correlated with indoor air pollution and heat stress symptoms among workers. Similarly, MECS' field visits to a large-scale institutional kitchen in Nairobi revealed evidence of heat accumulation. This facility, one of the largest kitchens in Africa, prepares tens of thousands of school meals daily using a steam cooking system powered by locally supplied briquettes. The kitchen is equipped with multiple large-capacity steam stoves for meal preparation and additional fryers for frying operations Despite the utilisation of exhaust systems and open ventilation, the kitchen remains extremely hot during cooking periods, with the accumulation of steam in the upper parts of the kitchen, making it challenging to cool down the environment effectively. This heat build-up, compounded by the size and intensity of operations, contributes to a stressful thermal environment for the kitchen staff.

Figure 19: Commercial kitchen in Nepal. (Source: Sieff and Todd, 2024)

Figure 20: Institutional cooking using gas cookers in Nepal (Source: Practical Action, 2023)

The economic implications of managing heat in such settings are thus substantial. The need for continuous cooling systems, such as air conditioning or advanced ventilation systems, increases operational costs for institutions and businesses. In light of the excessive heat gains in commercial kitchens, Simone et al. (2013) highlight the need for nearly year-round space cooling, which significantly impacts energy consumption and operating expenses. Transitioning to modern energy and heat efficient cooking technologies could help reduce both heat output and cooling costs.

For kitchen workers, prolonged exposure to high temperatures often results in thermal discomfort and health risks. Liu et al. (2020) measured the skin temperatures of 16 chefs preparing identical dishes in a kitchen under typical summer conditions using gas stoves. Their study revealed a highly non-uniform thermal environment, with air temperatures in the kitchen rising up to 5.3 °C during cooking. While they proposed an improved ventilation system to mitigate these effects, no interventions were proposed for the cooking appliances, despite their being the primary source of heat generation. Similarly, Singh et al. (2016) found that continued heat exposure in commercial kitchens can lead to alterations in kidney function and other heat-related health issues among kitchen workers. A study by Melaku et al. (2024) on hospitality kitchen workers in Ethiopia found that over 67% experienced heat stress symptoms, including heat exhaustion, fatigue, dizziness, nausea, muscle spasms, and even fainting, with factors such as poor ventilation, the use of wood fuel, and inadequate heat mitigation practices contributing to their vulnerability.

In light of such health considerations, **some studies have highlighted the limitations of applying general thermal comfort standards, typically used for office environments, to maintain health and safety in kitchen/cooking spaces.** These studies contend that thermal comfort standards such as ASHRAE Standard 55 and ISO Standard EN 7730 are not directly applicable to kitchens due to their non-uniform thermal environments, characterised by radiant heat from appliances and convective heat from cooking processes (Luo et al., 2023; Simone et al., 2013). For example, Simone et al. (2013) report that **a 5.5°C increase above neutral thermal conditions in commercial kitchens could result in a 30% loss of productivity**, underscoring the critical need for tailored thermal comfort criteria for kitchen spaces. Thermal comfort in a kitchen environment is mainly driven by the radiant heat that directly impacts the comfort of the workers, and by convective loads from both hooded and un-hooded cooking appliances. As such, the authors contend that understanding thermal comfort in commercial kitchens necessitates consideration of **thermal dissatisfaction** that can be caused by an overall thermal sensation that is too warm (i.e., the percentage people dissatisfied, PPD) or the percentage dissatisfied by local thermal discomfort (PD) due to draught, vertical temperature gradient, radiant asymmetry, or warm or cold floors.

To summarise, unlike domestic kitchens, institutional and commercial cooking spaces are generally part of the formal economy, making them subject to occupational health and safety (OHS) standards in many contexts (Anua et al., 2021; Ierardi and Pavilonis, 2020). However, **in many low- and middle-income countries in developing economies, such thermal comfort standards may be poorly implemented, inconsistently enforced, or in some cases, may not exist at all, leaving workers in these spaces highly vulnerable to health and safety risks**. Moreover, existing thermal comfort criteria are often inadequate for the unique conditions of these environments (Luo et al., 2023; Simone et al., 2013). As urban areas continue to expand, addressing the heat impacts of large-scale cooking operations will be essential for promoting health, safety, and sustainability in cities. There is an urgent need for tailored solutions that address both heat mitigation and worker safety. Integrating modern energy cooking solutions with improved infrastructure and tailored OHS standards can create more resilient cooking environments that benefit both workers and the broader urban environment.

6.3. Comparing Electric and Gas Cooking: Implications for Heat Stress

While much of the existing research on environmental and health impacts of cooking has focused on biomass fuels due to their prevalence and significant adverse impacts, fewer studies have directly compared electric and gas cooking— two fuels that are commonly considered ‘clean’. However, as gas and electric cooking technologies become more prevalent in urban settings, understanding their differing implications for heat stress is critical for informing policy and designing interventions. Both domestic and institutional kitchens offer valuable contexts for such comparisons, highlighting how these cooking technologies impact thermal environments, heat generation, health, and energy use. This section reviews the limited but growing body of literature comparing gas and electric cooking, with a focus on thermal comfort and heat stress, to provide useful insights for future policy and research.

Studies consistently demonstrate that **gas cooking (i.e. natural gas, LPG or other flammable fuels like bioethanol) produces higher thermal strain compared to electric cooking**, primarily due to the open flame and greater radiant heat. Haruyama et al. (2010) examined subjective thermal strain in 126 commercial and institutional kitchens in Japan, finding that gas kitchens exhibited significantly **higher ambient temperatures (29.6°C), mean radiant temperatures (MRT), and wet-bulb globe temperatures** compared to electric kitchens (25.7°C). Additionally, localised hotspots, such as areas around kettles, ovens, and stoves, were substantially hotter in gas kitchens, with temperatures reaching 36.4°C, 44.9°C, and 38.1°C, respectively, compared to 24.8°C, 39.5°C, and 27.1°C in electric kitchens. **Workers in gas kitchens reported higher perceptions of thermal discomfort, with male workers showing a fivefold increase and women workers a tenfold increase in perceived thermal strain** compared to workers in electric kitchens.

In domestic settings, where air conditioning is often unavailable, the heat emissions from gas cooking can lead to substantial indoor temperature rises, further exacerbating heat stress. Li et al. (2024) conducted a controlled comparison of gas and electric cooking under a unified cooking heating effect (CHE), where the heat gained by the substance in the pot was held constant across both methods. The study found that gas cooking produced higher temperatures and radiant heat fluxes across different parts of the body. Notably, radiant heat from the open flame increased abdominal exposure to heat, contributing to a greater risk of thermal discomfort compared to electric cooking (Figure *21*). Moreover, **gas cooking required higher air conditioning loads to maintain thermal comfort**, while electric cooking, particularly when combined with air conditioning, achieved better thermal environments with lower energy consumption, as well as lower carbon emissions (25% reduction compared to gas).

Domestic kitchens in low-income urban areas often lack adequate ventilation or cooling infrastructure (Giwa et al., 2022; Zhang et al., 2021). This is particularly problematic for gas cooking, as evidenced by anecdotal findings from the MECS eCookbook project in India. During the controlled cooking tests, it was observed that the use of ceiling fans became problematic during LPG cooking due to flame interference. Thus, to ensure safety and effective cooking, the fan had to be turned off, which made the cooking environment uncomfortable for the cook, leading to heat stress. In such contexts, the adoption of electric cooking technologies, such as electric pressure cookers (EPCs) and induction stoves, could significantly reduce indoor heat gains and improve thermal comfort.

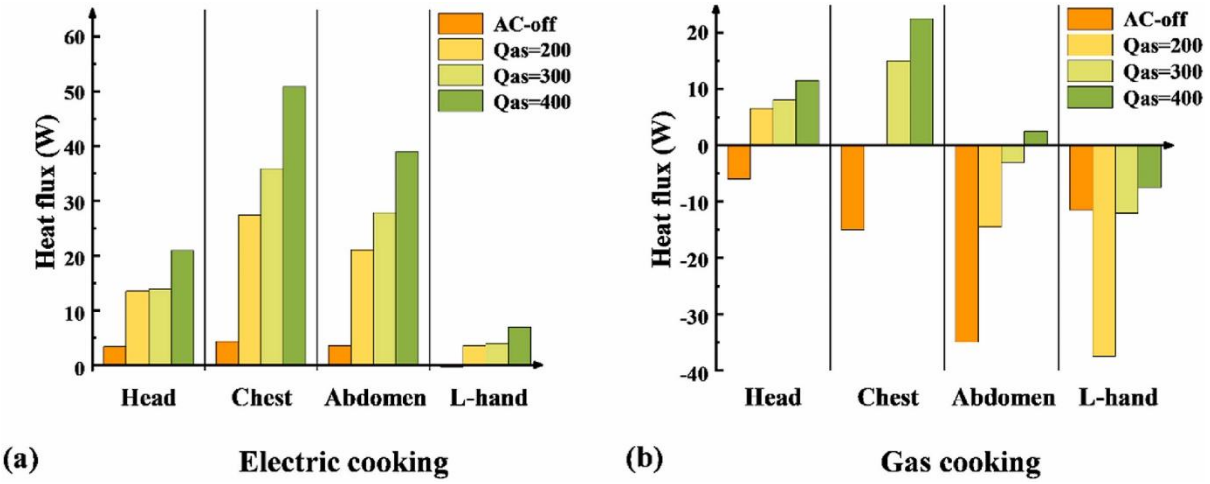

Figure 21: Experimental results showing heat transfer in critical body areas under different air conditioning air supply rate in electric (a) versus gas cooking (b) (Source: Li et al., 2024)

Electric induction cooking technologies offer significant advantages in reducing heat emissions compared to gas. Luo et al. (2023) demonstrated that in full-scale experimental setups**, replacing gas stoves with induction cooktops reduced air temperature rises around cooks from 8–9°C to just 1–2°C**. Similarly, mean radiant temperature increases dropped from 7°C to approximately 2°C with induction cooking. The study further highlighted that **vertical temperature gradients, a key contributor to thermal discomfort, were significantly more pronounced in gas cooking (up to 7°C difference)** compared to induction cooking, where no such gradients were observed. **Radiant heat exposure, particularly around the abdomen and lower arms, was significantly reduced with induction cooking, by as much as 88% on average**. In terms of overall kitchen ambient temperatures, gas cooking resulted in increases of up to 2.5°C, while no significant temperature changes were observed with induction cooking. These findings reinforce the potential of induction and eCooking technologies not only to enhance thermal comfort but also to reduce heat stress for cooks in both institutional and domestic settings.

7. Tackling urban heat stress in cooking: theoretical perspectives

The previous sections show that cooking heat stress can vary significantly based on the cooking method, types of fuel used, the nature of cooking (domestic versus institutional), cooking durations, the food selected and types of cuisines, the cook's heat tolerance and thermal comfort preferences, as well as the indoor and outdoor environmental conditions, building characteristics, neighbourhood densities and urban morphologies. From the very physiological characteristics of the gendered human body to the geo-political distributions of urban densities and infrastructures, urban heat stress emerges in socio-spatially distinct forms and requires a multi-level and multifaceted strategy for mitigation. This section will explore some of the practice theoretical and STS (Science, Tehcnology and Societies) literature and feminist perspectives that can provide greater insights into understanding the issue and designing interventions for tackling cooking heat stress. Here, it is worth acknowledging that energy justice also provides a critical and complementary framework for understanding and addressing this issue. Energy justice frameworks (e.g., Bombaerts et al., 2019; Jenkins et al., 2016) focus on equitable access to energy, the fair distribution of energy burdens and benefits, and the recognition of historically marginalised voices in energy decision-making (e.g., Castán Broto et al., 2018; Lewis and Pattanayak, 2012; Rahut et al., 2024; Standal et al., 2024), and hence provide a critical lens for analysing and addressing cooking heat stress, although not explored in further detail in this report.

7.1. A Social Practice Theory and Multi-Level Perspective approach

Heat stress resulting from cooking practices is a complex issue intricately linked to cultural norms, technological adoption, material infrastructures, and institutional policies. A combined framework of Social Practice Theory (SPT) and the Multi-Level Perspective (MLP) provides a comprehensive lens to understand how cooking practices emerge, persist, and can be transformed. This section explores how integrating the granular analysis of SPT with the system-wide dynamics of the MLP can offer valuable insights into mitigating heat stress through transformative shifts in cooking practices.

SPT posits that social practices, rather than individual agency or overarching social structures, are the fundamental units of social order, reproduction, and change (Reckwitz, 2002; Schatzki, 2001, 1996). Practices are viewed as organised, recognisable, and socially shared bundles of activities that are formed of complex interwoven social and material components that together constitute everyday life and social action (Shove et al., 2012). **This approach shifts the analytical focus away from individual choices- the focal point of most behaviour change theories- towards the routine activities that constitute everyday life.** Such a viewpoint elucidates how individual choice is often overridden by actions that are determined by habit, routine and the broader socio-material context rather than intention (Warde, 2005). As such, pro-environmental transitions and patterns of consumption are not dependent on simply educating or persuading individuals to make better choices, rather on transforming practices so as to make them more sustainable (Hargreaves, 2011; Scott and Powells, 2020).

According to Schatzki (1996), practices are ‘coordinated entities that are temporally unfolded and spatially dispersed nexus of doings and sayings’ (1996, p. 89). These socially shared and materially mediated activities (Schatzki, 2001) are inherently interconnected and evolve through their daily performance, shaped by cultural, social, and material infrastructures. **Practices like cooking, as organised set of actions, are held together by constitutive elements**, which Shove et al. (2012) identify as **materials** (e.g., stoves, fuels), **meanings** (e.g., cultural norms about food preparation), and **competences** (e.g., skills and knowledge about cooking). In the context of urban cooking, this perspective highlights how **heat-intensive cooking practices are sustained by a web of equally important and interconnected dynamics** (Halkier, 2009), including traditional cooking methods, inadequate ventilation systems, and entrenched gender norms that disproportionately expose women to heat stress. This conception of *distributed agency* (Sahakian and Wilhite, 2014) across people, things and social contexts recognises that successful transitions can only occur if addressing all these interconnected elements. For instance, the persistence of biomass or gas cooking is driven not only by cultural preferences for certain flavours or cooking methods (Akintan et al., 2018), but also by structural barriers such as limited access to clean fuels or efficient and affordable appliances (Grimsby et al., 2024; Malakar et al., 2018a).

Cooking, as a practice, is dynamic and continuously performed, redefined, and negotiated. Halkier (2009) emphasises that cooking is not a static or uniform activity; rather, it evolves constantly, varying across contexts and shaped by a myriad of socio-material factors. By focusing on the complexities of cooking, Halkier illustrates how cultural expectations and social negotiations— such as what constitutes ‘good’ cooking or contextually appropriate methods— play a pivotal role in shaping and sustaining cooking practices. This fluid and context-dependent nature of cooking underscores the importance of examining its broader socio-material dimensions when considering interventions, such as the transition to sustainable cooking practices or efforts to mitigate heat stress.

Practice theories redefine the problem of sustainability by focusing on how energy consumption occurs and evolves within the context of everyday practices, such as cooking, commuting, and heating homes (Strengers and Maller, 2015). Rather than treating consumption as an end in itself, it is understood as a by-product of these practices and their social organisation (Shove et al., 2012). This perspective shifts analytical attention away from individual preferences or specific goods and services, towards understanding how products and technologies are appropriated and integrated into socially ordered routines. Such a conceptual shift reframes notions of demand, need, and want as the outcomes of the practices that shape daily life (McMeekin and Southerton, 2012). Individuals are thus seen as practitioners— carriers of practices— whose actions reproduce and sustain these practices within the bounds of collective norms and material conditions. Technologies, in this framework, act as crossing points for multiple practices, enabling changes in one practice to influence others (Gram-Hanssen, 2011). Hence, unlike most energy studies, which often focus on improving access to energy through techno-economic interventions, **SPT provides deeper insights into how the adoption of modern energy services is influenced by social and cultural factors**, such as tradition (Akintan et al., 2018; Jagadish and Dwivedi, 2018), history (Kesteren and Evans, 2020) and taste (Warde, 2014), as well as the institutional and material frameworks that shape energy practices (Hand and Shove, 2007). This perspective is particularly relevant for addressing heat stress, which arises as a by-product of cooking practices that involve specific technologies and methods and occur within specific spatial and infrastructural contexts. By focusing on the interconnected dynamics of practices, SPT highlights how transitions to modern energy services can be designed to address the cultural, material, and institutional barriers that perpetuate energy-intensive and heat-intensive cooking practices.

Heat stress from cooking often emerges as a result of complex links between macro-scale food systems, technology networks, infrastructure disparities and social inequalities, and the micro-scale routine performances of everyday cooking and related practices. For example, Kesteren and Evans (2020), in their analysis of the effectiveness of healthy cooking interventions, demonstrate that non-cognitive elements involved in cooking at home often lead to unhealthy eating, and are formed of complex interlinks between social deprivation, diet and cooking practices. Social determinants are often linked to health-related practices, including cooking. Drawing parallels with such studies that focus on health and cooking, it is recognised **that a shift in heat-intensive cooking practices requires a shift in many adjacent bundled activities and practice elements**, including cooking fuel technologies, cooking methods and related comfort practices and techniques.

Significant work has been undertaken on cooking from a practice-theoretical perspective. For example, Malakar et al. (2018a, 2018b) show that inertia in cooking practices with solid fuels in India is intertwined with structural elements, such as established traditions, traditional income generating practices, gender norms, and a sense of belonging, which create persistence in the use of solid fuels, despite the availability and adoption of modern alternatives. Their SPT approach reveals that focusing only on supply side issues or standalone technology projects without considering broader social barriers limits the success of intervention projects. Wang and Bailis (2015) show how the kitchen and culture of food and cooking in India is driven by two interrelated social forces- the caste system and the drive for modernity. In this, the removal of traditional chulha cookstove is a socio-political process, with lower caste and marginalised households more readily willing to dissociate themselves from traditional cookstoves and the social stigma tied to them. Similarly for Tanzania, Grimsby et al. (2024) demonstrate that multiple fuel-use is driven not only by the complementary nature of the material qualities offered by different fuels like charcoal and LPG, but also because of social factors, such as saving money and coping with low and fluctuating incomes while securing household energy supply. Iessa et al. (2017) use a practice theoretical analysis to identify four issues as to why solar cooker technologies have not achieved large-scale success: overlooking local needs, considering existing socio-cultural cooking practices as obstacles, a pro-solution bias favouring solar cooker technologies irrespective of whether the proposed solutions align with actual needs, and a lack of methodologically sound impact studies that often fail to capture the complexity of cooking practices, household dynamics, and gender roles.

An SPT approach shows that a cooking transition for mitigating heat stress is not just about switching one technology or one fuel with another. It requires understanding how existing cooking practices are embedded within wider socio-technical systems. For example, in Nigeria, Akintan et al. (2018) find that ethnic-specific cultural norms and taboos significantly influence cooking practices and fuel choices, often outweighing concerns about health risks from household air pollution. Similarly, Halkier and Jensen (2011)**,** in their study of food and cooking habits among Pakistani Danes, show that even when clear knowledge and awareness of healthy diets is available, food and cooking practices are negotiated in terms of the pleasures of taste, cultural expectations of appropriate food, managing of family time and gendered relations.

Heat-intensive cooking is often bundled with other practices, such as heating, ventilation, and household organisation. SPT recognises these linkages, suggesting that interventions must consider the broader nexus of practices. For instance, Mguni et al. (2020) employ SPT to analyse cooking practices within the urban water-energy-food nexus in informal settlements in Kampala, Uganda. They highlight how household energy poverty shapes cooking performances, such as avoiding energy-intensive foods or deferring water boiling due to charcoal scarcity. By zooming in on cooking, the study captures the agency of human actors and the skills, resources, and decisions they mobilise daily. Zooming out connects these individual practices to larger systems of provision. This multi-scalar lens reveals the ways social networks, cultural norms, and economic constraints mediate resource access and consumption. In a similar vein, Castán Broto et al. (2020) demonstrate that in Mozambique, income alone does not determine fuel choice. Cultural and generational factors, taste preferences, and social variables like convenience and family structures influence the persistence of charcoal use. Such studies provide lessons for understanding how vulnerabilities in cooking can intersect with systemic heat-related challenges, offering pathways for designing interventions that not only reduce cooking-related heat emissions but also address broader social inequities. By **integrating clean cooking technologies into urban resilience strategies,** such interventions can align with cultural norms, enhance resource access, and contribute to more sustainable urban living environments.

SPT directs attention to the routinised everyday practices at the micro- and meso-level focusing on change and continuity in the horizontal circulation and integration of different practice elements. On the other hand, socio-technical transitions literature focuses on theorising aggregate trends and multi-level dynamics in systems change (Greene, 2018). Hence, **combining SPT with the Multi-Level Perspective (MLP) enhances the understanding of how practices interact with larger socio-technical systems** (Hargreaves et al., 2013; McMeekin and Southerton, 2012). **The MLP conceptualises socio-technical transitions across three vertical levels** (Geels, 2002): 1) **niches:** these represent the micro-level and the locus for radical innovations. Niches are protected spaces where innovations can develop without being immediately exposed to the pressures of the regime or landscape. Within the cooking sector, these can include pilot projects for eCooking technologies or the introduction of efficient EPCS or induction stoves that reduce heat losses to the environment; 2) **socio-technical regimes**: these represent established practices and associated rules that stabilise existing systems. As such, regimes are often resistant to change, maintaining the status quo through vested interests and entrenched routines. This meso-level includes established norms, institutions, policies, and infrastructure. For example, widespread reliance on biomass and gas cooking technologies is supported by existing infrastructure, markets, and cultural preferences; 3) and an exogenous **landscape**: this represents the broader macro-level context that shapes the socio-technical system. It evolves slowly and creates pressures or opportunities for change within the system. It sets the stage for transitions by challenging or reinforcing the stability of the regime. External factors such as climate change, economic trends, and political developments that are beyond the control of actors within the system. In the context of cooking and heat stress, this can include urbanisation processes, fossil fuel industrialisation and the UHI effect that exacerbate heat stress from cooking, but also the global recognition of climate change that can create a demand for sustainable and thermally efficient cooking technologies.

By combining SPT and MLP, Hargreaves et. al. (2013) reveal how practices and regimes cross over and intersect with one another in innovation processes. Hence, researchers can "zoom in" on the daily performance of cooking practices and "zoom out" to understand how these practices are shaped by and can influence broader socio-technical regimes and landscapes. Hargreaves et al. (2013) illustrate this integrated approach by analysing a niche-level innovation— a sustainable food cooperative— and its challenges in scaling up and transforming the dominant supermarket-driven food regime. They show how deeply entrenched systems, such as those of labour availability and food storage infrastructures, and adjacent practices, such as recruitment of farmers to organic production, can hinder the diffusion of sustainable practices. **Applying this framework to heat stress from cooking can reveal how entrenched cooking practices are supported by existing energy regimes (e.g., gas infrastructure), urban processes (densely populated and informal settlements) and entrenched cultural practices (e.g., cooking methods tied to flame-based systems)**. For instance, as the AFREC report (2024) outlines, the continued reliance on biomass fuels or LPG is sustained by market structures, energy policies, and social expectations. Nevertheless, the combined SPT-MLP lens also identifies potential intervention points. Targeted efforts to promote low-heat cooking practices could leverage pressures from the landscape level, such as global momentum for decarbonising energy systems, public health policies focused on reducing indoor air pollution, and urban building retrofitting for improved thermal comfort. By **aligning niche innovations like eCooking technologies with supportive socio-technical regimes and cultural practices**, such interventions can create synergies, paving the way for transitions that reduce heat stress while enhancing sustainability and equity.

McMeekin and Southerton (2012) similarly argue that integrating the hierarchical insights of the MLP with the horizontal, practice-oriented focus of SPT offers a robust framework to understand the interplay between system-level transitions and the everyday practices that sustain them. This dual perspective enables a nuanced analysis of how broader socio-technical regimes and landscapes influence, and are influenced by, the micro-level dynamics of daily life. Specifically, they highlight three key areas for effective sustainability interventions: the role of social relations in shaping final consumption, the interdependencies between production and consumption systems, and the ways technologies become integrated into everyday practices. When applied to heat stress, this **integrated approach underscores the importance of addressing both the horizontal and vertical dimensions of change**. On the horizontal plane, policies must target the transformation of entrenched cooking practices, including fuel preferences, cooking methods, and cultural norms. For example, shifting from heat-intensive cooking to clean technologies like induction stoves requires reconfiguring materials, meanings, and competences central to cooking practices. On the vertical plane, systemic shifts in socio-technical regimes, such as transitioning energy systems to support widespread adoption of electricity-based cooking or updating building codes to improve kitchen ventilation and thermal comfort, are critical.

Hence, a combined SPT-MLP framework to mitigate heat stress in cooking can provide greater insight into:

- **Analysing cooking practices:** understanding how materials (e.g., inefficient stoves, cooking spaces and kitchen arrangements), competences (e.g., skills in traditional cooking methods), and meanings (e.g., cultural importance of certain cooking practices) contribute to heat stress, and how heat-intensive cooking perpetuates– from the continued use of certain cooking fuels, methods and technologies.
- **Addressing adjacent practices:** Considering how changes in cooking practices might influence or require changes in other practices, such as comfort and ventilation, household organisation, and gender roles.
- **Identifying systemic intersections**: recognising how cooking practices interact with socio-technical regimes (e.g., energy infrastructure, housing design) and landscapes (e.g.,

urbanisation, climate change) and how these can reinforce heat-intensive cooking practices and pose barriers to sustainable cooking solutions.

- **Designing interventions at multiple levels**:
    - Niche innovations: promoting and supporting new technologies like EPCs or induction stoves in protected spaces to encourage experimentation and adoption.
    - Regime shifts: advocating for policy changes, infrastructure development, and market adjustments to support clean cooking technologies.
    - Landscape pressures: leveraging global concerns about climate change and health to create momentum for systemic change.

7.2. A Feminist approach

Heat is not uniformly distributed, and heat stress does not impact everyone equally. **Heat vulnerability and exposure, including from cooking, is significantly higher for certain groups in certain regions and geographies**. These disproportionate impacts of heat are not only based on regional climatic and socio-demographic disparities, but are exacerbated by inadequacy of services, precarity of infrastructure and insufficient access to cleaner and more efficient technologies. **Feminist perspectives provide a powerful lens to address the intersecting inequalities that shape exposure to cooking heat stress**, particularly for marginalised groups like women. By situating heat stress within the broader dynamics of care work, energy systems, and socio-technical practices, a feminist approach emphasises justice, equity, and sustainability, moving beyond technocratic or market-driven solutions.

A feminist perspective provides a means for understanding how power works within the energy system, in its various cycles of production, consumption and distribution (Bell et al., 2020; Wilson, 2018). It interrogates the power dynamics and socio-political structures that perpetuate energy inequality and environmental harm, particularly for excluded and vulnerable groups. Although feminist approaches are concerned with tackling systemic injustices and inequities for all marginalised social groups, most feminist literature has focused on women and their limited access to resources and empowerment because of their subordinated societal role.

Revaluing women’s care work in cooking

Evidence highlights the deeply gendered dimensions of cooking heat stress. Women are not only biologically more susceptible to greater heat vulnerability and thermal strain but are also disproportionately responsible for cooking, especially in domestic settings, exposing them to heightened risks of heat stress. Globally, gender is the most significant predictor of cooking responsibilities (Gallup, 2023). **Home cooking remains a gendered practice**, with the global gender gap in cooking growing to **4.7 meals per week** in 2022. In some countries, particularly in the Global South, this gap is even wider, with women preparing an average of **8 more meals per week** than men (Gallup, 2023). Beyond gender differences, cooking practices are also shaped by socio-demographic characteristics. The global Gallup survey on home cooking reveals that larger households, comprising five to seven or even eight or more members, rely significantly more on home-cooked meals, averaging 10.5 and 10.4 meals per week, respectively. These households also exhibit the widest gender gaps in cooking responsibilities. The data further shows that **individuals with the lowest levels of educational attainment and those belonging to the poorest 20% income quintile depend most heavily on home-cooked meals** (Gallup, 2023). Notably, these trends align with increasing gender disparities, highlighting how financial constraints limit dining-out options and place greater cooking burdens on lower-income women. Consequently, these women experience heightened exposure to the health and heat impacts of conventional polluting fuels.

This trend also corresponds with broader data on heat stress, which demonstrates that vulnerability is influenced by intersecting identities of gender, class, education, occupation, and geographical location (see Section 0). Evidence indicates that heat stress disproportionately affects individuals with lower incomes, limited education, and women (Green et al., 2019; Haruyama et al., 2010; Mukhopadhyay and Weitz, 2022). Furthermore, studies show that elderly and low-income women often encounter significant barriers to accessing cleaner sources of energy (Buechler et al., 2020). An intersectional feminist analysis sheds light on how these overlapping factors—gender, economic status, and energy access—interact to exacerbate health risks and perpetuate inequities.

Despite being the primary users of domestic cooking technologies, studies reveal that women often lack decision-making power in the purchase and use of these technologies, with such decisions frequently undertaken by men (Alda-Vidal et al., 2023; Chidziwisano et al., 2024; Khalid and Foulds, 2021; Petrova and Simcock, 2019). Feminist Marxist scholars argue that women's constrained agency in fuel choices and limited participation in income-generating activities perpetuate traditional, heat-intensive cooking practices such as using firewood (Malakar et al., 2018a).

Cooking, embedded within traditional gender roles and as an essential aspect of care work, forms part of women's unpaid reproductive labour. From a 'devaluation perspective' (England, 2005), care work is associated with the private sphere and, by extension, with women, leading to its marginalisation and reduced value in societal and economic systems (Hooks, 1984a; Lewenhak, 1992). Cultural norms that diminish women's contributions reinforce this undervaluation. Markets further exacerbate this disparity by failing to reward care work as a public good (England, 2005), leaving domestic cooking and its subsequent heat and health impacts largely overlooked. Excluded from the formal economy, **women's unpaid domestic labour has long been ignored in discussions about energy access and climate change** (Bell et al., 2020; Damgaard et al., 2022; Gonda, 2016). Even in institutional settings and the hospitality sector, feminist studies reveal how feminised industries and roles are systematically undervalued, further entrenching these inequities.

Energy systems function as "structures of power and exclusion" (Cho et al., 2013, p. 797), shaping who benefits from and who is burdened by available energy technologies. Ecofeminism ties the exploitation of women and nature to patriarchal and capitalist structures, as environmental challenges disproportionately affect women in underdeveloped regions due to their marginalised roles in society and the economic structures that limit their access to resources (Gaard, 2011). **A feminist perspective challenges these systems' traditional focus on growth, efficiency, and profit, advocating instead for justice, care, and well-being**. Feminist critiques highlight how cooking practices and kitchen spaces are often overlooked in energy and urban planning, as they are associated with women's domestic roles and seen as peripheral to public infrastructure investments. For instance, studies show that even as household incomes improve, investments in kitchen spaces, particularly ventilation, often lag behind (Wang and Bailis, 2015), further entrenching vulnerabilities.

A feminist approach calls for the recognition of this invisible labour and the prioritisation of interventions targeting the improvement of modern energy cooking services, particularly where they impact women. **Reducing cooking heat stress through clean cooking technologies and innovative financing mechanisms represents a crucial step towards economic restructuring that prioritises well-being over profit**. Such interventions, when designed with women's agency and needs at the centre, align with the principles of a care-based energy transition (Damgaard et al., 2022; Gram-Hanssen, 2024; Groves et al., 2021). Such efforts can not only mitigate the adverse health and heat impacts of cooking but also address systemic inequities, contributing to a more just and inclusive energy economy.

Seeing the kitchen through a feminist lens: tackling cooking heat stress

A feminist approach highlights the social and spatial dimensions of energy systems and infrastructure transitions (Khalid and Lemanski, 2024), including the critical role of kitchens. **Within feminist literature, cooking and kitchen spaces are often framed as sites of complex power dynamics** at the intersection of gender, domesticity, and space (Craik, 1989; Martens and Scott, 2017; Reiheld, 2008; Silva, 2000; Wang and Liang, 2018). Kitchens, as both physical and symbolic spaces, serve as sites where gender identities are performed, contested, and negotiated. Depending on how technology and social norms intersect, kitchens can act as spaces of empowerment or constraint for women.

Early feminist critiques often depicted cooking and related practices as inherently oppressive, tying them to the drudgery of unpaid domestic labour under the gendered norms of domesticity (Cowan, 1983; Hayden, 1980). As spaces of unpaid reproductive work, women's engagement with food and kitchens has often been devalued, seen as routine, or even oppressive (DeVault, 1994; Friedan, 1963). **Some feminist campaigns have even advocated for "kitchenless" houses** (Hayden, 1980), **reflecting a desire to socialise domestic work and dismantle its gendered association** by taking it out of the house and into the formal economy.

However, **others** (e.g., Fürst, 1997; Hooks, 1984; Meah, 2014) **have viewed kitchen spaces as sites of potential creativity, skill development, resistance, and empowerment.** These scholars argue that kitchens are not merely spaces of routine and ritual reinforcing gendered roles but also arenas where women can subvert and remake these roles to assert agency. Meah's (2014) analysis of domestic kitchens across different geographical contexts contrasts the Anglo-American second-wave feminist discourse, which often views kitchens as spaces of oppression, with narratives from the Global South that emphasise their potential for agency and resistance. According to the author, in contexts of extended kinship networks, kitchens provide women with spaces for expressing identity and exercising agency within survival politics.

Abarca (2006) also conceptualises kitchens as spaces of dynamic freedom and self-awareness, where subjectivities and agency can emerge. Simon et al. (2021) similarly argue that food preparation does not just involve repetitive tasks but also moments of creativity and cultural preservation. Kitchens serve as spaces where women negotiate their identities and take pride in their roles as nurturers and caretakers, creating meaningful social connections. In their study of community kitchens in Jharkhand, India, Mahato and Vardhan (2021) showcase how women, through these kitchens, became part of micro-entrepreneurial ventures, experiencing self-esteem and contributing economically and socially to their families and communities. **Kitchens thus became sites of collective action, decision-making, and empowerment.** Similarly, exploring the business of home-cooked meal delivery in India, Gooptu and Chakravarty (2018) illustrate how women leveraged their cooking skills to generate income and gain social recognition, while reshaping perceptions of domestic cooking, transforming it into a valued skill within a professional context. Miseres (2022) similarly highlights how culinary practices and kitchens have been reclaimed as spaces for empowerment, cultural expression, and political engagement in Argentina, challenging patriarchal norms and nurturing community and identity formation. Stovall et al. (2015) advocate for a feminist-environmental discourse on the kitchen, emphasising its potential as a space for social and environmental education. **By connecting sustainable food practices with feminist values, they propose a more inclusive view of kitchen work as integral to addressing broader societal challenges like climate change and food justice.**

Gregson and Rose (2000) argue that spaces like kitchens are not merely containers of power relations but active participants in producing and reproducing them. **Viewing spaces as performative highlights how kitchens can be instrumental in shaping gender roles and, simultaneously, offer possibilities for re-negotiating them.** Fuller and Löw (2017) similarly conceptualise space as socially constituted, continually shaped by interactions, practices, and meaning-making. From this perspective, kitchens can be envisioned as extensions of multiple socio-spatial processes, acting as both sites of constraint and connection, of empowerment and subjugation (Schroeder, 2006; Way, 2021). Recognising this performative dimension underscores the need to address not only the social but also the spatial dynamics of kitchen spaces, especially when examining women's experiences and relationships with cooking in the context of heat stress. Poor ventilation and inadequate design, particularly in low-income urban areas, exacerbate women's exposure to extreme heat. By **reimagining kitchens not just as functional spaces but as transformative ones, interventions can integrate clean cooking technologies with improved ventilation, better spatial design, and culturally sensitive approaches**. This perspective also highlights the need for such strategies to empower women—not just as passive recipients but as active agents and decision-makers in reshaping kitchen spaces and practices.

Through a feminist lens, tackling cooking heat stress becomes a multi-dimensional challenge that requires acknowledging the gendered nature of kitchens, recognising their potential as sites of social change, and integrating technologies and designs that prioritise well-being, empowerment, and equity. By doing so, kitchen spaces can evolve into sites that alleviate, rather than exacerbate, the physical and emotional burdens of cooking, ultimately contributing to broader gender equity and sustainable energy transitions.

Rethinking cooking technologies through a feminist lens

The intersection of technology, gender, and cooking practices highlights both the transformative potential of modern energy solutions and the limitations of technocentric approaches. Access to electricity has been shown to benefit women's care work practices by enabling them to perform their expected roles more efficiently while improving various domestic tasks (Standal and Winther, 2016). Similarly, **modern energy cooking services have demonstrated transformative benefits by reducing the burden of fuel collection, lowering the risk of sexual violence during firewood collection, saving time, and expanding opportunities for women in education and employment** (Akter and Pratap, 2022; Khalifa, 2024; Sharma et al., 2023). These interventions also alleviate some of the physical and time-intensive aspects of domestic labour, empowering women and enabling their participation in broader social and economic activities (Khalid et al., 2024; Winther et al., 2017). However, as Standal and Winther (2016) argue, **these benefits often fail to address entrenched gender relations.** Nevertheless, some examples exist where women's roles in cooking technology projects have transcended being mere end-users or beneficiaries. Women have been empowered as change agents and decision-makers across the energy supply chain, shaping solutions and driving innovation (ENERGIA, 2019, 2017). This demonstrates the importance of including women not just in the design and implementation of energy solutions but also in leadership roles within energy transitions. The MECS gender equality framework (Khalifa, 2024) similarly highlights the critical need to address structural inequalities that hinder women and marginalised groups from fully benefiting from modern energy cooking services. By focusing on access, resources, agency, and an enabling environment, the framework offers actionable insights to integrate gender dimensions into clean cooking initiatives (Figure 22).

The adoption and use of cooking technologies are influenced by deeply gendered norms, as "gender is at work in the world of technologies" (Silva, 2000, p. 612). In many contexts, patriarchal structures perpetuate disparities in energy technology adoption, with men often making decisions about the purchase and use of technologies despite women being their primary users (Chidziwisano et al., 2024; Johnson et al., 2020; Khalid and Razem, 2022; Majid and Mustafa, 2022; Wiese, 2020). Silva (2000) critiques the technological determinism in narratives about cooking innovations, which often fail to consider the real-world social contexts in which these technologies are embedded. For instance, innovations like thermostat-controlled ovens have historically invisibilised and devalued women's contributions to cooking, framing them as passive users rather than active participants.

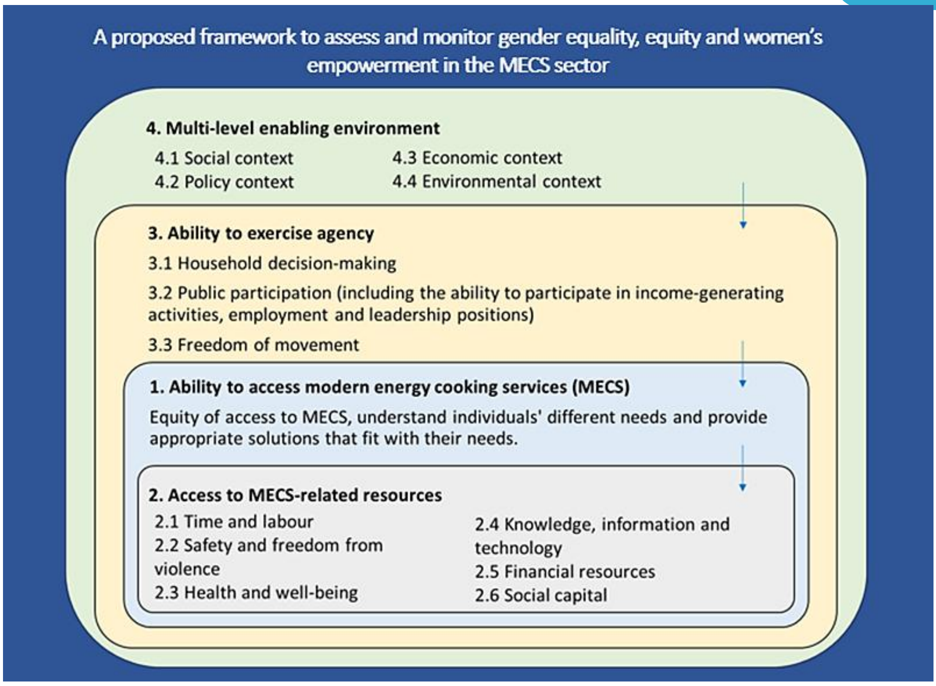

Figure 22: Proposed framework to assess and monitor gender equality, equity and women's empowerment in the MECS sector. Source: *(Khalifa, 2024)*

Moreover, technological innovations frequently exacerbate gendered inequities when they fail to align with users' lived realities. For instance, studies in Malawi (Chidziwisano et al., 2024) reveal that while women preferred electrical appliances for their ease, they often resorted to more cost-effective charcoal methods to support household financial priorities dictated by men. This conflict between saving time and saving money underscores the complexities of fuel choices within gendered dynamics. Similarly, technologies marketed as "intelligent" often overlook the cultural and practical needs of users, resulting in limited impact (Silva, 2000).

A feminist approach to technology design and policymaking critically examines and dismantles the gendered assumptions that underpin these innovations. It challenges designers and policymakers to question who is envisioned as the primary user, what roles they are expected to perform, and how these assumptions shape the design and adoption of technologies. For example, Khandelwal et al. (2017) show how improved cookstove initiatives in India failed because they undervalued the cultural significance of traditional chulhas and overlooked the broader socio-economic implications of transitioning away from subsistence labour. For many women, "freedom" from labour-intensive practices does not necessarily equate to empowerment, as alternatives often involve precarious and poorly rewarded work. Similarly, Gonda (2016) critiques the prioritisation of technologies over practices in climate change adaptation projects, warning that such approaches risk reinforcing patriarchal norms rather than challenging them.

Empirical studies also reveal that the persistent underperformance of technologies such as solar cookers stems from their failure to align with local socio-cultural contexts. For example, Iessa et al. (2017) show that imposing solutions without co-creating interventions with local communities leads to limited uptake. **Feminist approaches advocate for co-creation processes that ensure technologies meet the specific needs, preferences, and aspirations of users, particularly women. A feminist lens also emphasises the relational and ecological dimensions of energy technologies.** Lorenz-Meyer (2017), for instance, explores solar energy projects through a feminist technoecological framework, illustrating how solar initiatives intersect with social and ecological systems. She highlights systemic exclusions in technology development, such as the marginalisation of certain communities and limited involvement of local labour. Her work underscores the importance of embedding an ethos of care, responsibility, and collaboration into technology projects to create more inclusive and sustainable solutions.

These lessons are directly applicable to addressing cooking heat stress, which is intertwined with systemic issues like poor ventilation, urban heat, and inadequate energy access. Feminist interventions must advocate for systemic changes, including improved kitchen designs, modern energy services, and climate-responsive urban policies. Importantly, they must move beyond focusing solely on technology to engage with the socio-cultural practices and power dynamics that shape how technologies are used and understood.

A feminist energy systems' approach to tackling cooking heat stress

Recognising the inadequacy of mainstream technocratic energy systems in addressing issues of equity and justice, **Bell et al. (2020) advocate for a comprehensive, whole-systems approach to feminist energy systems, organised around four intersecting dimensions: political** (emphasising democracy, decentralisation, and pluralism); **economic** (prioritising human well-being and biodiversity over profit and unchecked growth); **socio-ecological** (favouring relationality and interconnectedness over individualism); and **technological** (championing distributed, decentralised power systems and community-driven innovation). Their framework underscores the need for decentralised, community-led energy systems rooted in care, relationality, and biodiversity rather than profit and individualism.

Adopting this framework for addressing cooking heat stress presents an opportunity to rethink the challenges and solutions from a feminist perspective. As outlined in Table 2, this approach shifts the focus from narrowly defined, techno-centric interventions to systemic changes that recognise the intersecting inequalities and systemic oppressions that perpetuate cooking heat stress. **Feminist energy systems aim to create equitable and transformative pathways that prioritise justice, sustainability, and community-led solutions.** By acknowledging the socio-political, economic, and cultural contexts in which cooking heat stress is embedded, this approach offers a way to address the issue in a more holistic, inclusive manner.

Table 2: A feminist energy systems' approach to tackling cooking heat stress

Dimension	Key issues	Feminist approach
Political	• Urban cooking policies often neglect informal settlements, where the majority of heat stress-related challenges occur. • The framing of energy access as a market problem instead of a human right exacerbates inequalities.	**Energy democracy**: Advocate for the democratic ownership and governance of urban energy systems, ensuring that marginalised communities have a voice in decision-making processes. **Legislative protections**: Implement and enforce building health and safety standards in domestic settings and occupational health and safety standards in institutional and commercial cooking spaces, particularly in informal urban economies where workers are most vulnerable to heat stress. **Redistributive justice**: Allocate public funding for retrofitting homes and kitchens with clean energy solutions in low-income urban areas. Feminist approaches highlight the need for redistributing resources to address historical injustices. **Global solidarity**: Leverage international climate and development funds to address urban cooking heat stress, ensuring that solutions prioritise equity and accountability.
Economic	• Heat stress often disproportionately affects low-income households reliant on inefficient and heat-intensive cooking methods (e.g., biomass, kerosene).	**Redefining energy access**: Prioritise affordability and access to clean cooking technologies as a public good rather than a market commodity. Feminist energy systems advocate for subsidies or free provision of clean cooking technologies to low-income households.

	• Urban residents in informal settlements often face high energy costs and limited access to clean cooking solutions.	**Decentralised economic models**: Support cooperative ownership models for energy systems, such as community solar initiatives, that reduce dependency on centralised, profit-driven utilities. **Care-centric policies**: Recognise cooking as a care-oriented labour that sustains households and communities. Policies should ensure that time and physical burden associated with cooking in extreme heat are alleviated through accessible technologies. **Labour market reforms**: Provide economic incentives to women entrepreneurs to promote clean cooking solutions in their communities, enabling economic empowerment while addressing heat stress.
Socio-Ecological	• Gendered inequalities often leave women disproportionately burdened by heat stress from cooking in poorly ventilated urban kitchens. • Cultural and societal norms may influence the adoption of clean cooking technologies.	**Intersectional interventions**: Acknowledge and address the compounded vulnerabilities of gender, class, race, and urban informality. Programmes should be tailored to meet the specific needs of diverse groups of urban residents. **Community participation**: Engage women and other marginalised groups in the design and implementation of cooking solutions. This ensures technologies and policies are culturally appropriate and socially acceptable. **Education and advocacy**: Use community-driven campaigns to raise awareness about the health impacts of heat stress and the benefits of clean cooking technologies. Feminist perspectives emphasise knowledge-sharing and peer education. **Ecologies of care**: Promote urban design that integrates communal cooking spaces with heat-resilient features (e.g., shaded areas, natural ventilation) to foster social interaction while mitigating heat stress.
Technological	• Inefficient cooking technologies (e.g., biomass stoves) produce high levels of heat and pollutants, exacerbating indoor and outdoor heat stress. • Technological solutions often fail to account for social and cultural contexts, limiting their adoption.	**Human-centred design**: Develop clean cooking technologies that prioritise user needs, particularly those of women, who are the primary cooks in many urban households. Features could include reduced heat emissions, faster cooking times, ergonomic designs and RE-based eCooking technologies. **Decentralised solutions**: Promote distributed renewable energy systems, such as solar-powered EPCs and induction stoves, which reduce dependency on centralised grids and offer heat-resilient cooking options. **Climate adaptation technologies**: Introduce energy-efficient ventilation systems and reflective building materials in cooking spaces to lower ambient temperatures. **Inclusive innovation**: Support collaboration between engineers, designers, and communities to co-create technologies that are affordable, durable, and adaptable to diverse urban settings.

A feminist approach to tackling cooking heat stress requires moving beyond simplistic binaries—such as clean-dirty, public-private, virtue-vulnerability, nature-culture— towards strategies that embrace complexity, plurality, and context-specific solutions. Instead of universal prescriptions for transitioning to clean cooking fuels or technologies, **this approach emphasises situated, place-based, and multi-fuel strategies tailored to the unique needs and aspirations of different communities.** It acknowledges that solutions must address intersecting oppressions, such as those based on gender, class, and geography, to ensure transformative outcomes. **By centring justice, equity, and sustainability, feminist energy systems aim to empower communities, especially women, not as passive recipients of clean energy solutions but as active participants and agents of change.** Although gender equity and women's empowerment may not always be the primary goal of such initiatives, they emerge as critical outcomes of a system designed to generate collective well-being, inclusivity, and resilience. In this way, feminist energy systems offer a framework for addressing the systemic drivers of cooking heat stress while advancing broader goals of energy justice and environmental sustainability.

8. The way forward- tackling heat stress through MECS

Cooking heat stress is a multi-faceted issue that requires a whole-system's transition approach. Modern energy cooking services offer a critical component within this transition for addressing heat stress in urban cooking environments. Transitioning to clean cooking technologies can provide potential pathways toward mitigating heat-related challenges, particularly in densely populated urban areas where traditional cooking methods exacerbate thermal stress. This concluding section summarises some of the key gaps in current research on cooking and urban heat stress and provides direction for future MECS research.

8.1. Current gaps and opportunities in the heat stress discourse and linkages with clean cooking

Despite growing awareness of urban heat stress, significant gaps remain in linking this phenomenon with cooking practices.

- **Underrepresented role of cooking in UHI and heat stress studies:**

  Current urban heat discourse primarily emphasises the built environment, transportation, and industrial heat emissions (Tong et al., 2021), often **overlooking the significant contribution of domestic and institutional cooking to urban thermal loads**. For instance, data on the impact of cooking-related activities on anthropogenic urban heat emissions and the UHI effect remain largely unavailable, and cooking interventions are notably absent from UHI mitigation strategies. Even initiatives like the UN-Habitat's Chief Heat Officers programme, which aims to address heat as a growing public health threat and enhance urban resilience, do not currently consider modern energy solutions such as clean cooking technologies as part of their climate-response strategies. This landscape study underscores the potential of eCooking technologies to not only reduce heat stress and enhance thermal comfort for both end-users and kitchen workers but also significantly lower cooling loads and reliance on air-conditioning. **Findings from MECS indicate that eCooking is more compatible with mechanical ventilation systems, such as ceiling fans, offering a less energy-intensive alternative for maintaining indoor comfort.** Additionally, eCooking can improve indoor environments in institutional settings like schools, enabling the integration of kitchen spaces within school buildings without posing health risks to occupants.

- **Insufficient focus on thermal comfort:**

  Research on indoor environments primarily addresses air quality concerns arising from biomass cooking (Kansiime et al., 2022; Lachowicz et al., 2022; Smith et al., 2007) but often neglects the heat stress caused by cooking practices. **Investigations into thermal comfort in kitchens are scarce** and focus primarily on HVAC interventions (Liu et al., 2020; Zhang et al., 2021). **Alternative cooking technologies, such as eCooking appliances, can substantially mitigate heat stress and enhance thermal comfort in kitchen spaces**. Their improved heat transfer efficiencies, coupled with advantages like reduced cooking times and automation, can contribute to creating a more comfortable and efficient cooking environment.

- **Limited data on cooking-related heat emissions:**

  Understanding the thermal performance and heat transfer efficiency of different cooking technologies is complex since heat loss from cooking is influenced by various technical and social aspects of the cooking practice. Quantifying heat emissions from cooking technologies can also be challenging (Smith, 1989; Smith et al., 2007), particularly in households employing fuel stacking. **Completely electric kitchens are rare, making it difficult to isolate the thermal impact of specific technologies**. This is likely a contributing factor to why heat stress has not been directly associated with inefficient cooking practices and why proposed solutions often fail to recommend transitioning to eCooking technologies. However, **advancements in technologies such as digital Monitoring, Reporting, and Verification (dMRV) systems and IoT-enabled devices offer new opportunities to integrate environmental monitoring into eCooking appliances, enabling more accurate calculations of heat emissions** and paving the way for strategies to mitigate heat stress.

- **Overlooked health impacts of heat stress:**

  Whilst significant research on cooking fuels and technologies focuses on the health impacts, indoor air quality and pollutant emissions from inefficient cooking technologies, **much less focus is given to the direct and indirect impacts of cooking heat emissions on health**. For example, whilst WHO's (2011) public health guidelines on preventing health effects of heat highlight the hazards of biomass combustion, they lack emphasis on the heat-related health impacts associated with cooking, nor provide guidance for transitioning to clean cooking solutions as a way to reduce heat stress. This omission leaves a critical gap in developing health-centric clean cooking policies. **Integrating heat stress mitigation into cooking-related health policy frameworks** can help in promoting technologies like eCooking that improve health, reduce emissions, and enhance thermal comfort.

- **Overlooked role of institutional and commercial kitchens:**

  Institutional settings like schools and hospitals and commercial kitchens in high-density urban areas face acute heat challenges (Ierardi and Pavilonis, 2020; Melaku et al., 2024; Nsengiyaremye and Khalifa, 2023). These environments often **operate for extended hours with large-scale cooking demands, yet their contributions to heat stress remain understudied**. A greater focus on institutional and commercial cooking in research and policy can help in better understanding their role in exacerbating or mitigating heat-relate challenges.

- **Distributional and gendered dimensions of cooking and heat stress:**

  Cooking heat stress is disproportionately distributed across geographies and socio-economic groups and influenced by infrastructural and spatial inequities. Low-income households in informal settlements, for instance, often rely on poorly ventilated kitchens, limited cooling options, and inefficient cooking fuels, compounding the harmful effects of high temperatures. Within these underserved contexts, multiple axes of inequality—such as gender, age, and ability—create layers of vulnerability. **Women, who are predominantly involved in cooking activities** (Gallup, 2023), **face disproportionate exposure to heat stress** (Anua et al., 2021; Glass et al., 2015). Despite this, clean cooking strategies often fail to incorporate justice concerns and gender-sensitive interventions, thereby overlooking an opportunity to address both heat stress and broader social inequities, such as those tied to gendered labour divisions. **Integrating a socio-technical, feminist and justice-based approach** is essential for achieving equitable and effective solutions at the intersection of gender equity and sustainable urban development.

8.2. Future MECS research avenues

To address these gaps, a robust MECS research agenda is needed to tackle the complex issue of cooking heat stress in urban environments. Below are proposed some key research aims and questions to guide future studies:

1. **Quantifying heat contributions of cooking practices:**
    - How do different cooking technologies (e.g., biomass, gas, electric) and different cultural practices related to cooking contribute to indoor urban heat loads?
    - What proportion of building or urban heat emissions can be attributed to cooking activities, and how does this vary by fuel type?
    - What are the thermal efficiency profiles of emerging cooking technologies, such as EPCs and induction stoves?
    - What are the thermal dynamics in large-scale institutional and commercial cooking environments?
2. **Evaluating health, gender and other co-benefits of clean cooking:**
    - What are the specific health outcomes of reducing heat stress through modern energy cooking services, particularly for women and vulnerable groups?
    - How can a transition to modern energy cooking services alleviate heat-stress for women, and what implications can such a transition have for improved gendered outcomes and gender relations?
    - How can transitioning to eCooking improve thermal comfort and reduce heat-related illnesses in low-income and informal urban settings?
3. **Integration of cooking in urban heat mitigation strategies:**
    - How do different cooking technologies interact with different kitchen/cooking spaces and how does this interaction impact cooking heat stress?
    - Can clean cooking technologies be incorporated into broader sustainable building design, urban planning and UHI mitigation strategies?
    - What role can eCooking play in reducing cooling loads and improving thermal comfort in residential and institutional buildings?
4. **Designing socio-technical heat stress interventions:**
    - What socio-cultural, behavioural and gender-responsive interventions can promote the adoption of clean cooking technologies? How can these be integrated with sustainable cooking spaces and kitchen designs?
    - How can existing metrics for cooking efficiency be expanded to include thermal comfort and heat stress considerations?
    - How can institutional and commercial spaces transition to clean cooking technologies while maintaining operational efficiency and reducing heat stress for workers?

Addressing these gaps and prioritising a focus on tackling cooking heat stress can provide a potential pathway for MECS to further highlight the role of eCooking technologies in sustainable future urban development. This research can also open pathways for integrating clean cooking solutions into urban planning and public health policies to alleviate thermal stress and also enhance energy efficiency and resilience in urban areas, especially in developing economies of the Global South. This approach can catalyse a broader transition toward sustainable energy systems while addressing the critical intersection of cooking, health, and the built environment.

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