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ACCELERATING THE IMPLEMENTATION OF ELECTRIC COOKING IN LOW- AND MIDDLE-INCOME COUNTRIES

Tesis doctoral

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Clean cooking is an ‘orphan’ sector. Even though it cuts across a broad array of sectors— energy, health, environment, climate, gender, social protection, finance, rural and urban development, and private-sector development, amongst others— clean cooking is not prioritized by any of these sectors.

Yabei Zhang

Table of contents

Resumen

En 2019, el número de personas sin acceso a servicios energéticos asequibles, fiables y modernos para cocinar (MECS) ascendía a unos 4.000 millones, más de la mitad de la población mundial, y las consecuencias de la falta de MECS son muy relevantes. En 2019, 2,31 millones de personas murieron prematuramente como consecuencia de la contaminación del aire en los hogares asociada al uso de estufas con biomasa, el 4% de todas las muertes en el mundo. La recogida de leña y carbón vegetal de forma insostenible agrava los problemas de deforestación y contribuye al cambio climático. Las mujeres suelen dedicar más tiempo a la recogida de leña, el cocinado y su limpieza asociada, y se ven más afectadas por la mala calidad del aire interior.

El Objetivo de Desarrollo Sostenible 7, aprobado por las Naciones Unidas en 2015, busca "Garantizar el acceso a una energía asequible, segura, sostenible y moderna para todos". Sin embargo, los avances en el acceso a las MECS son muy lentos, y con las políticas y compromisos actuales, el número de personas sin cocinado limpio se reducirá en menos del 10% en 2030, por lo que es imprescindible un cambio radical en los próximos años para alcanzar ese objetivo.

El cocinado con electricidad (eCooking) ha avanzado en los Países de Renta Baja y Media (LMIC) desde un 3% del total en 2000 (140 millones de personas) hasta un 7% en 2019 (450 millones), pero aún está lejos de alcanzar su potencial y acercarse a las cifras de los países desarrollados (por ejemplo, 70% en España). El principal objetivo de esta tesis es acelerar la transición a la eCooking en los LMIC, proporcionando información sobre el cocinado eléctrica y una metodología, probada en un estudio de caso, para fomentar el despliegue de estas tecnologías mediante la planificación eléctrica.

La transición al eCooking se producirá sustituyendo progresivamente los sistemas de cocinado existentes, en algunos casos, conviviendo durante un tiempo varios sistemas en el mismo hogar. Con el fin de conocer en detalle la información necesaria para abordar la transición a la eCooking y sus impactos, el capítulo 2 analiza los principales sistemas de cocinado y su conceptualización, describiendo las opciones de eCooking, revisando los principales impactos y cómo se miden, analizando las prácticas de cocinado habituales y concluyendo con una propuesta de asignación de tareas de cocinado al eCooking para conseguir un cocinado eficiente.

La planificación de la electrificación es fundamental para lograr el eCooking y el acceso a la electricidad. Aunque los modelos geoespaciales de electrificación tienen una larga trayectoria en la literatura, su uso para MECS está en una fase incipiente. Para conocer cómo debe modelarse la demanda de eCooking para la planificación de la electrificación y cuáles serían los impactos de su incorporación en la electrificación de zonas aún no electrificadas, el capítulo 3 desarrolla el caso concreto de la electrificación del distrito de Nyagatare, en Ruanda. Una vez presentado el contexto, se desarrolla una metodología para establecer los posibles escenarios, los perfiles de demanda, el análisis de costes y la estimación de los impactos sobre las emisiones de gases de efecto invernadero y la deforestación, utilizando el Reference Electrification Model (REM), una herramienta geoespacial de planificación.

La transición a MECS se ve afectada por muchos factores, como las políticas públicas, el desarrollo del mercado y de la industria, la disponibilidad de combustibles alternativos, el entorno físico, la asequibilidad de los hogares, las necesidades y las percepciones de las personas que cocinan. Para saber qué medidas pueden facilitar la transición al eCooking, el capítulo 4 analiza los factores que han influido en otros procesos de transición de cocinado e identifica un conjunto de medidas para promover la transición del eCooking.

Como resultado de la investigación, se puede observar que los impactos de la cocina son altamente contextuales y dependen de muchas variables; por lo tanto, extrapolar datos de un contexto a otro supone el riesgo de incorporar un gran margen de error, y en muchos casos, es necesario realizar un trabajo de campo para obtener datos fiables.

El estudio de caso del distrito de Nyagatare indica que la metodología desarrollada proporciona información útil para ayudar a la toma de decisiones. La hipotética penetración de la cocina eléctrica cambiaría sustancialmente la fracción de hogares con cada modo de electrificación y conduciría a una reducción del coste del kWh. El eCooking puede ser competitivo en costes en comparación con el gas licuado de petróleo para los hogares conectados a la red. La sustitución de la leña y el carbón vegetal por la electricidad es un medio eficaz para lograr la reducción de las emisiones de GEI.

Se han identificado 57 medidas para promover el eCooking para generar un entorno propicio, apoyar a la industria, y satisfacer las necesidades de los usuarios y de la comunidad.

El documento concluye proponiendo futuras investigaciones con vistas a facilitar la estimación de los impactos de la cocción mediante encuestas rápidas, completar el Reference Electrification Model (REM) con un modelo que incorpore con más detalle combustibles que compiten con la electricidad, y las necesidades y preferencias de los usuarios, y realizar varios estudios de casos nacionales para medir la viabilidad, el impacto y el coste-beneficio de las medidas identificadas.

Abstract

The number of people without access to affordable, reliable and modern energy cooking services (MECS) was around 4 billion in 2019, more than half of the world's population, and the consequences of the lack of MECS are significant. In 2019, 2.31 million people died prematurely as a result of Household Air Pollution (HAP) associated with cookstoves, 4 per cent of all deaths worldwide. The gathering of firewood and charcoal in an unsustainable manner exacerbates deforestation problems and contributes to climate change. Women often bear a greater burden in terms of collecting firewood, cooking and cleaning, and they are more affected by HAP.

Sustainable Development Goal 7, approved by the United Nations in 2015, seeks to "ensure access to affordable, reliable, sustainable and modern energy for all". However, progress on access to MECS is very slow, and given the current policies and commitments, the number of people without clean cooking facilities will be reduced by less than 10% by 2030. A radical change in the coming years is imperative to meet the desired goal.

Cooking with electricity (eCooking) has advanced in Low- and Middle- Income Countries (LMIC) from being 3% of the total cooking in 2000 (140 million) to 7% in 2019 (450 million), but it is still far from realising its potential and nearing the figures of developed countries (e.g., 70% in Spain). The main objective of this thesis is to accelerate the transition to eCooking in LMICs providing comprehensive information about electric cooking and a methodology, tested in a case study, to foster the deployment of these technologies through electrification planning.

The eCooking transition will occur by progressively replacing existing cooking systems, even with a coexistence for some time several in some households. To know what information is needed to address the eCooking transition in a comprehensive way and ascertain its impacts, Chapter 2 analyses the main cooking systems and how they have been conceptualised, describing in detail the eCooking options, reviewing the main impacts and their measurement, analysing common cooking practices, and concluding with a proposal for allocating cooking tasks to obtain an efficient cooking.

Electrification planning is critical for the achievement of eCooking and electricity access, because eCooking increases significantly the demand of low-income households with low electricity consumption. Planning is also necessary because eCooking would compete with other technologies, in cost, convenience, and health and environmental impacts. Although geospatial electrification models have a long trajectory in the literature, their use for MECS is at an incipient stage. Chapter 3 develops the specific case of the electrification of Nyagatare District, in Rwanda to know how the eCooking demand for electrification planning should be modelled and what the impacts of incorporating eCooking in the electrification of areas not yet electrified would be. Once the context has been presented, the methodology for establishing possible scenarios, demand profiles, cost analysis and estimation of impacts on greenhouse gas emissions and deforestation are carried out using the Reference Electrification Model (REM), a geospatial electrification planning tool.

Cooking transition is affected by many factors, such as public policy, market and industry development, availability of alternative fuels, physical settings, household affordability, cookers' needs or perceptions. Chapter 4 analyses the factors that have influenced many cooking transition~~s~~ processes and identifies a set of measures to promote the eCooking transition.

As a result of the research, it can be noted that cooking impacts are highly contextual and depend on many boundary variables; therefore, extrapolating data between different contexts risks generating high levels of error. In many cases, fieldwork is required to obtain reliable data.

The Nyagatare District case study indicates that the methodology developed provides useful information to assist decision-makers. The hypothetical penetration of electric cooking would substantially change the fraction of households electrified with each electrification mode and lead to a reduction in the electricity cost. Electric cooking can be cost-competitive compared to Liquified Petrol Gas for grid-connected households. Even more, replacing firewood and charcoal with electricity for cooking is an effective means of achieving GHG emission reductions.

Fifty-seven measures have been identified to promote e-cooking to protect the environment, to support the industry structure and services, and to meet user and community needs.

The document concludes by proposing future research with a view to facilitating estimation of cooking impacts through rapid surveys, completing the Reference Electrification Model (REM) with a model for fuels that compete with electricity and customer's needs and preferences, as well as carrying out several national case studies to measure the feasibility, impact and cost-benefit of the measures identified.

List of figures

List of tables

Abbreviations

AQG	WHO Air Quality Guideline
BC	Black carbon
DALY	Disability-adjusted life years
eCooking	Electric cooking
EF	Emission factor
EPC	Electric pressure cooker
ESMAP	Energy Sector Management Assistance Program
GLM	Generalized logic model for clean fuel scale-up
GHG	Greenhouse gases
HAP	Household air pollution
HH	Household
ICS	Improved cookstove
IEA	International Energy Agency
LMIC	Low- and Middle-Income Countries
LPG	Liquefied petroleum gas
MECS	Modern Energy Cooking Services
MTF	Multi-Tier Framework
SDG	Sustainable Development Goals
SLCP	Short-lived climate pollutants
WB	The World Bank
WHO	World Health Organization
USD	US dollar

1. INTRODUCTION

1.1 The challenge of access to modern energy cooking services

<u>Modern energy cooking services access and electricity access</u>

The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDG) are the global plan, promoted by the United Nations and approved by most of the countries, to eradicate poverty and move towards a more sustainable world. SDG 7 seeks to "Ensure access to affordable, reliable, sustainable and modern energy for all", and its target 7.1. states that by 2030 access must be universal for everyone everywhere (UN General Assembly, 2015). SDG 7 is linked to all other 16 SDGs, and its achievement will help to achieve the whole 2030 Agenda (Figure 1). For example, access to electricity facilitates health services (SDG 3), improves education quality (SDG 4) and promotes industrialization (SDG 9). Clean cooking solutions contribute to reducing global mortality and improving overall wellbeing (SDG 3), promote gender equality and women's empowerment (SDG 5), make cities and human settlements safer, resilient and sustainable (SDG 11) and tackle climate change (SDG 13). Universal access also reduces inequalities (SDG 10).

Figure 1. Affordable and clean energy supports all Sustainable Development Goals. Source: IRENA, 2017.

Universal access to energy includes access for productive uses, for community infrastructure and for households. In the household, access is common considered in three main categories: access to electricity, access to energy for cooking, and access to energy for heating. The first two types of access involve the entire world population, and the third affects only those populations living in cold areas. Target 7.1. has two parts:

7.1.1., focusing on access to electricity, and 7.1.2., focusing on access to modern energy cooking services (MECS).

According to the custodian agencies of SDG 7, in 2019, 2.6 billion people were without access to clean cooking solutions (IEA et al., 2021). However, considering not only the cleanness but all the factors that define MECS, the number of people without access rises to 4 billion (ESMAP, 2020b). Sub-Saharan Africa is the region with the lowest percentages of people with access (Figure 2).

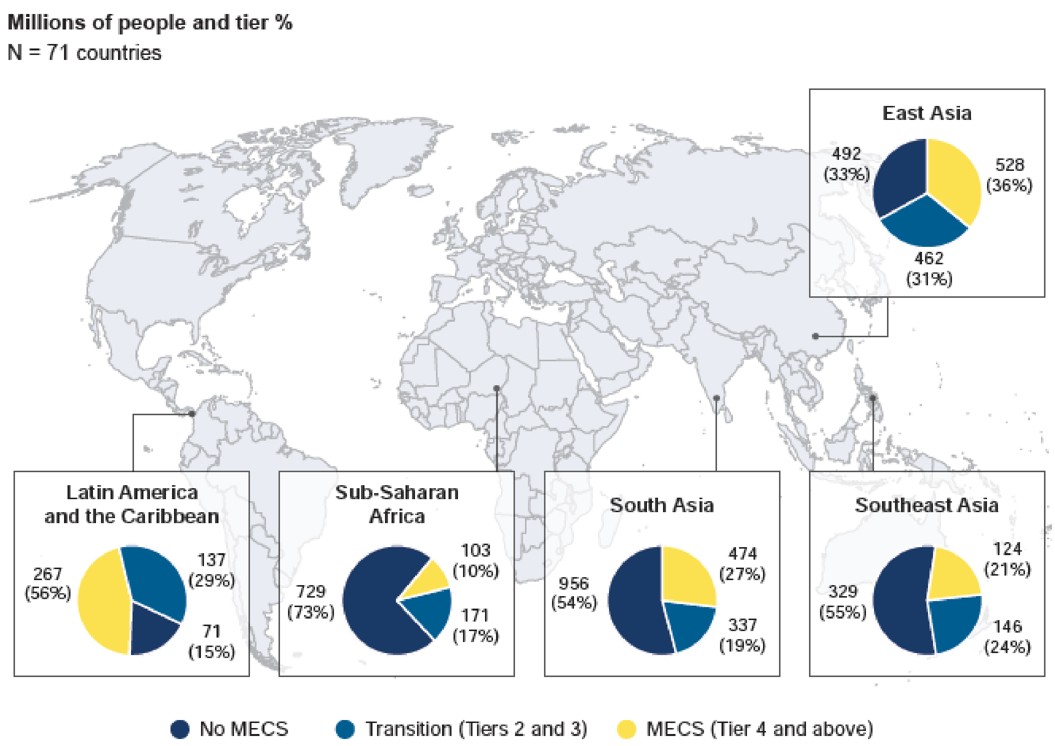

Figure 2. Population with access to MECS. Source: ESMAP, 2020b.

The consequences of the lack of MECS are significant. In 2019, 2.31 million people died as a result of Household Air Pollution (HAP) associated with cookstoves, 4 per cent of all deaths worldwide, and 91.5 million global disability-adjusted life years (DALYs) were lost (Bennitt et al., 2021). Health impacts are accompanied by the waste of time spent collecting firewood, cooking, and cleaning. Moreover, the gathering of firewood and charcoal in such an unsustainable manner exacerbates the deforestation problems and contributes to climate change. Women often bear a significant burden in terms of fuelwood collection and cookstove preparation and are consequently more affected by HAP. Therefore, addressing the lack of modern energy cooking services (MECS) yields important co-benefits and contributes not only to achieving SDG 7, but also SDG 3, “Ensure healthy lives and promote well-being for all at all ages”, SDG 5, “Achieve gender equality and empower all women and girls”, and SDG 13, “Take urgent action to combat climate change and its impacts”(Mazorra et al., 2020).

Progress on access to MECS is very slow. The number of people without access to clean cooking has only been reduced by 13% in the last decade (from 3 billion in 2010 to 2.6

billion in 2019). The rate has also decelerated since 2012, with a pace lower than population growth in some countries (ESMAP, 2020b). The International Energy Agency's Stated Policies Scenario, which reflects the policies and commitments of all countries around the world, estimates during the next decade that the number of people without clean cooking facilities will be reduced by less than 10% (2.4 billion by 2030) (IEA, 2020c).

Zhang (2021) considers that the difficulties in making progress are due to the fact that clean cooking is an "orphan" sector, as despite touching many sectors, it is neglected in national and international policies; "invisible", as the impacts are unknown or not present in national policies; and "expensive", as cooking is an energy intensive activity and biomass solutions are very contextual, which makes it difficult to achieve economies of scale.

Progress on electricity access is much faster. In 2019, there were 759 million people without electricity access (less than one third of those without access to clean cooking). Furthermore, in the last decade, the population without access has fallen by 37% (IEA et al., 2021). The 20 countries with the largest access deficits, accounting for 76% of the population without access, are concentrated in Sub-Saharan Africa and South Asia (Figure 3), and mainly in rural areas.

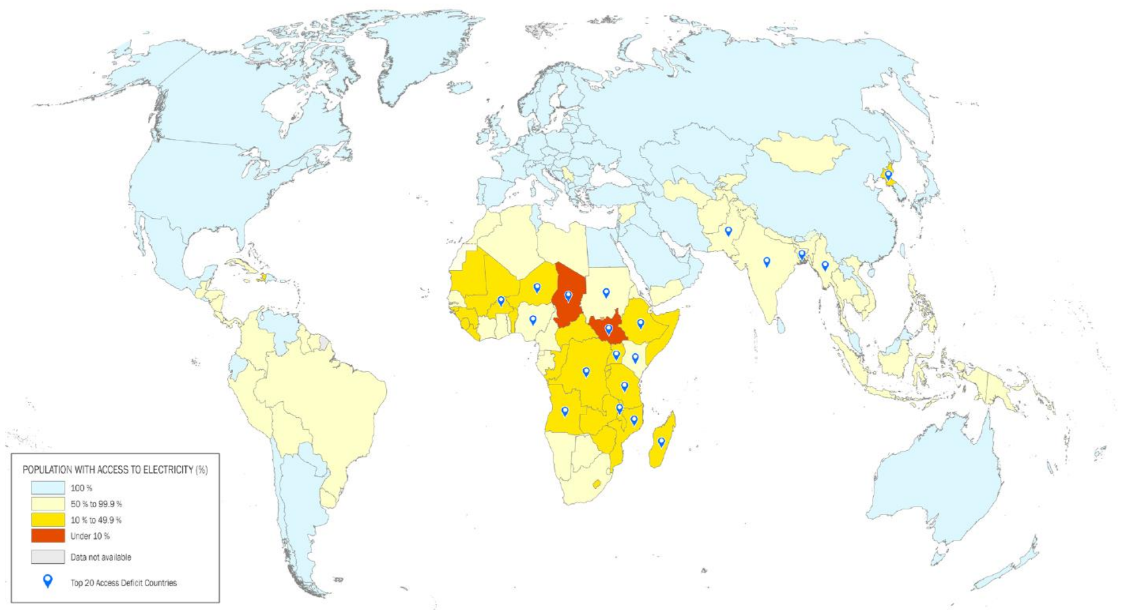

Figure 3. Percentage of population with access to electricity in 2019 by countries, and the 20 countries with the highest deficit. Source: IEA et al., 2021.

Cooking with electricity

In LMIC, the main energy sources are gas, mainly liquefied petroleum gas (LPG) and biomass. Figure 4 shows that gas dominates in urban areas while biomass dominates in rural ones. The general trend is an increase in the use of gas and electricity, and charcoal, and a decrease in the use of biomass, coal and kerosene.

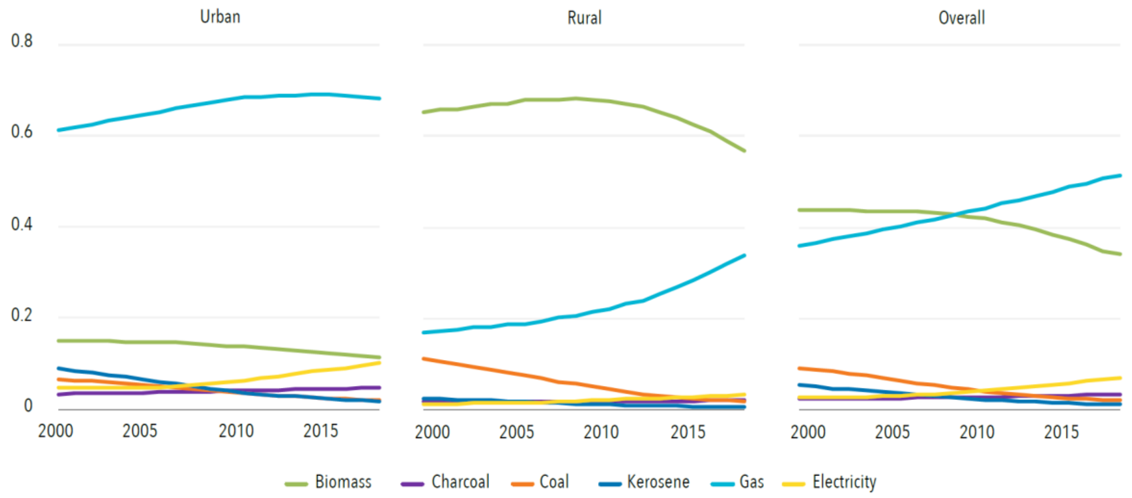

Figure 4. Percentage of population using biomass, charcoal, coal, kerosene, gas and electricity in urban areas, rural areas and overall, in LMIC. Source: IEA et al., 2021.

The main reason for the widespread use of firewood is that it can be collected for free or purchased at a low cost in many places. Charcoal replaces firewood in some urban areas when firewood must be purchased. The popularity of gas, mainly LPG, is because of its low cost and widespread availability, the opposite of electricity, which is more expensive in many countries and less available in rural areas. Coal is only used in countries where it is extracted, but it is not usually exported for cooking. The use of kerosene has been decreasing for some time and is generally replaced by gas. Dung and crop waste can have a relevant role in some rural areas, but their uses are not generalized. In many households, the use of multiple fuels is a common practice.

Although cooking with electricity (hereafter eCooking) has advanced in LMIC from 3% of the total in 2000 (140 million) to 7% in 2019 (450 million), it remains a low figure (IEA et al., 2021), with only a few countries and cities using it extensively (Figure 5). This contrasts sharply with the general situation in developed countries. For example, in Spain, 70% of households use electric cooking stoves, compared with 30% which use gas stoves and 5% which use both (CNMC, 2020).

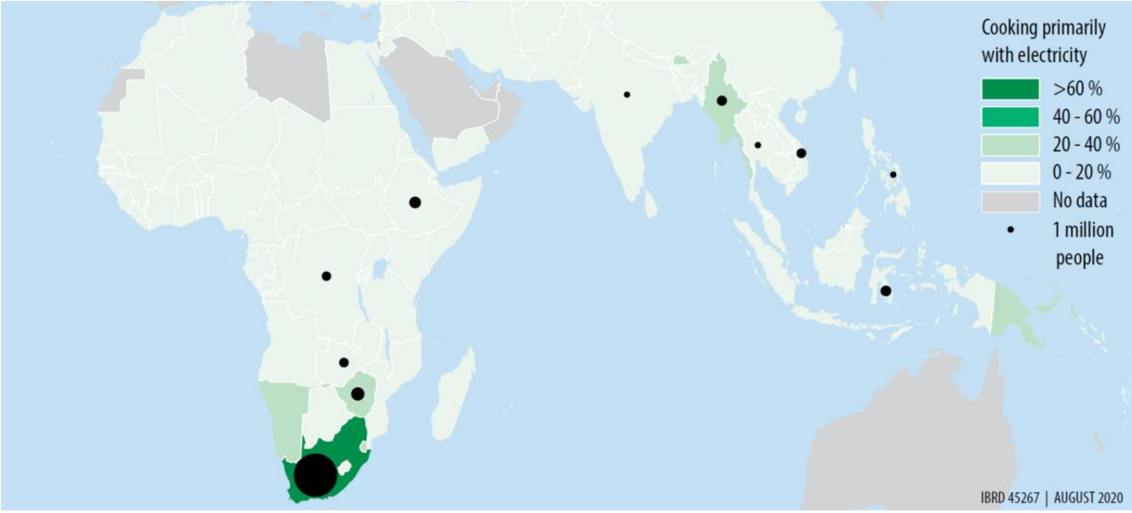

Figure 5. Percentage of households cooking primarily with electricity in Sub-Saharan Africa, South Asia and Southern Asia. Source: ESMAP, 2020a.

Historically, eCooking has only been considered suitable for affluent countries or healthy urban households (Smith & Sagar, 2014). Lack of electricity supply and the high cost of electricity have been considered the main barriers for spreading eCooking, but these factors do not fully explain the situation, as in many urban areas there has been a reasonable electricity supply during decades which has not prevented the use of electric appliances, and in other areas cooking with electricity can be more cost effective than other alternatives, especially if it is done with efficient equipment. On the other hand, eCooking was considered unrealistic because it was thought of in terms of cooking with electricity only, when the most frequent cooking transition process is cooking with several technologies simultaneously (ESMAP, 2020b).

Another important reason for the slow spread of eCooking has been the prioritisation of LPG as a clean solution. LPG has been the most promoted alternative, with strong support from governments and international organizations globally (Quinn et al., 2018). National LPG penetration targets for the coming years include, for instance, 58% of households in Cameroon, 50% in Ghana, and 35% in Kenya by 2030 (Puzzolo et al., 2020). However, in some African countries its expansion has come at the expense of high subsidies, which are difficult to maintain in the long term (IEA, 2014), and LPG is a non-renewable resource with non-negligible climate impacts (ERG, 2017). In fact, some developed countries have started to impose banning their use in future households (Ivanova, 2019).

The international perception of the potential of eCooking to address the cooking problem has changed rapidly in the last two years, in part thanks to the research and advocacy work being done by the MECS programme (MECS, n.d.). Institutions that influence and finance LMIC energy policy, such as the World Bank and the ESMAP program, have started to promote it, and the UN ministerial-level thematic forum side event held in June 2021 launched the call to action "40-60 by 2030", a call for 40% of households to use eCooking with 60% of the electricity supplied from low-carbon sources by 2030 (MECS, 2021c).

eCooking potential

Cooking with electricity permits the use of not only stoves or hobs, but also a wide range of appliances to allow a better adjustment to cooking needs, such as ovens, microwave ovens, toasters, rice cookers, slow cookers, pressure cookers, kettles, and so on. In addition, some of these appliances are highly energy-efficient, such as induction stoves that transmit energy directly to the cooking vessel or those with high thermal insulation, which reduce energy consumption by a factor of roughly seven compared to electric hobs (Couture & Jacobs, 2019). For example, electric pressure cookers (EPCs) enable the preparation of meals that traditionally require long boiling times, such as beans, which are a staple food in many countries, and which consume a large proportion of cooking energy. EPCs provide significant energy savings and could have a transformative role for cooking, similar to that of LED for lighting. However, cooking behaviour is determined and reinforced through everyday social interactions (Jürisoo et al., 2019), and the adoption of new technologies faces cultural barriers, the inertia of tradition, economic constraints, unwillingness to pay for new equipment, and external factors (Malla & Timilsina, 2014; Rehfuess et al., 2014).

In recent years some constraints that limited eCooking are being relaxed: access to electricity is accelerating, surpassing population growth since 2015 in Sub-Saharan Africa (IEA, 2014); the cost of power generation with renewable resources is dropping (IRENA, 2019); and photovoltaic panels are becoming ubiquitous globally. Some countries in Sub-Saharan Africa have surplus generation capacity to supply new demand (IEA, 2019b) and, in new areas to be electrified, the increase in household electricity demand will lead to a decrease in unit electricity cost. In this context, electric cooking is arousing new interest as a means of promoting electricity and MECS access simultaneously, thus “killing two birds with one stone” (Batchelor, Brown, Scott, & Leary, 2019).

1.2 Research aim and overview

The main objective of this thesis is to provide information on how to accelerate the transition to eCooking.

The eCooking transition will occur in a context where there are other systems that it will replace. It is therefore important to know what these systems are, why they are used, what impact they have, or what the usual cooking transition process is. In order to address these issues, research question 1 has been posed:

What information is needed to address the eCooking transition in a comprehensive way and ascertain its impacts?

To answer this question, Chapter 2 analyses the main cooking systems and how they have been conceptualised, describing in detail the eCooking options, reviewing the main impacts and their measurement, analysing common cooking practices, and concluding with a proposal for an eCooking allocation for efficient cooking.

Electrification planning is critical for the achievement of eCooking and electricity access, which requires a multidisciplinary approach that considers techno-economic, political, and regulatory factors (among others). Precise data and robust planning tools are critical for producing a realistic, implementable electrification plan. Although geospatial electrification models have a long trajectory in the literature (Bhattacharyya & Palit, 2021; Moner-Girona et al., 2018; Morrissey, 2019), their use for MECS is at an incipient stage (KTH, n.d.). To address this issue research question 2 is:

How should the eCooking demand for electrification planning be modelled and what would be the impacts of incorporating eCooking in the electrification of areas not yet electrified?

Chapter 3 addresses this issue by developing the specific case of the electrification of Nyagatare District, in Rwanda. After describing the context, the methodology for establishing possible scenarios, demand profiles, cost analysis and estimation of impacts on greenhouse gas emissions and deforestation are carried out. Using the Reference Electrification Model (REM), a geospatial tool of electrification planning, several simulations are carried out to analyse the sensitivity of the results with respect to the cost of grid-supplied electricity, the cost of photovoltaic equipment for off-grid systems, and the electricity demand for non-cooking services.

The cooking transition is modulated by many factors, such as public policy, market and industry development, availability of alternative fuels, physical settings, household affordability, cooker's needs or perception. To look more deeply into how these issues may affect the eCooking transition, research question 3 has been posed:

What measures can facilitate the eCooking transition?

Chapter 4 analyses the factors that have influenced many cooking transitions processes in order to see whether or not they are irrelevant to the eCooking transition. After reviewing the main analyses on barriers and drivers, factors related to the enabling environment, the structure of the industry and services, and the needs and perceptions of users and the community have been developed, proposals being made for each of them.

Conclusions are presented separately at the end of each chapter, and then there is a final chapter of conclusions to highlight the findings of the overall work. The document ends with a chapter of limitations and further research, and the list of references used.

2. INFORMATION TO ADDRESS THE ECOOKING TRANSITION

Research question: What information is needed to address the eCooking transition in a comprehensive way and ascertain its impacts?

This chapter is partially based on Sections 1 and 2 of the article authored by the author of the thesis and published in the journal Science of Total Environment Energies: "A comprehensive analysis of cooking solutions co-benefits at household level: Healthy lives and well-being, gender and climate change" (Mazorra et al., 2020), and some ideas have been discussed at the "Data Standards for Integrated Energy Planning Workshop" (SE4ALL, 2020).

This chapter reviews the main elements related to cooking systems, electric cooking, impacts, and practices in order to obtain a complete picture of the problem and to design eCooking programs and measure their impacts.

2.1 Cooking systems

2.1.1 Improved cookstoves

The most basic form of cooking is with open three-stone fires, tripod, flat mud ring or traditional charcoal stoves. These forms of cooking are often referred to as "traditional". Biomass cookstoves that enhance these systems are called improved cookstoves (ICS). The World Bank (Putti et al., 2015) distinguishes three types of ICS (Figure 6):

- Legacy and Basic ICS: Stoves based on traditional models with some improvements in efficiency, and generally handcrafted.
- Intermediate ICS: Mostly based on "Rocket" models and produced locally.
- Advanced ICS: Fan jet or natural draft biomass gasifiers. Sometimes they use briquettes or pellets.

(a) (b) (c) (f)

(e) (f)

(a) Three-stone fire; (b) Jambaar Bois; (c) Patsari; (d) Gasifier Prime Square; (e) Noflaye Jegg; (f) U type;.

Figure 6. Main ICS types. Sources: own elaboration with pictures a, b, c and f from de la Sota, 2017; and from Medina et al., 2019.

The main objective of the ICS is to reduce fuel consumption. Table 1 shows the typical energy efficiency of some stove models. However, the theoretical efficiency of ICSs is not always confirmed in reality. For example, in a comparative study between the three-stone fire and a basic ICS (Noflaye Jegg), no difference was found between their fuel consumption, 0.6 ±0.4 kg of fuel/kg food for both systems (de la Sota, 2017).

Table 1. Usual energy efficiency of main biomass cookstoves. Source: (World Bank, 2018).

ISO's voluntary performance targets / MTF Tier *	0	1	2	3	4	5
Stove efficiency	<10	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50
Stove type	Tree-stones fire, tripod, flat mud ring, traditional charcoal stove	Conventional or old generation ICS	ICS with chimney, rocket stove, ICS with insulation	Rocket stove with high insulation, advanced insulation charcoal stoves	Rocket stove with chimney (well-sealed), rocket stove gasifier, advanced secondary air charcoal stove, forced air	Electricity, solar, LPG

* ISO's voluntary performance targets / MTF Tier are explained in Section X.

Many ICS are based on the Rocket style; its structure consists of a simple combustion chamber and a vertical chimney, which improves the combustion of the fuel before the flame reaches the pot surface. Advanced models are thermally insulated, have a chimney, and prevent smoke escape (Figure 7).

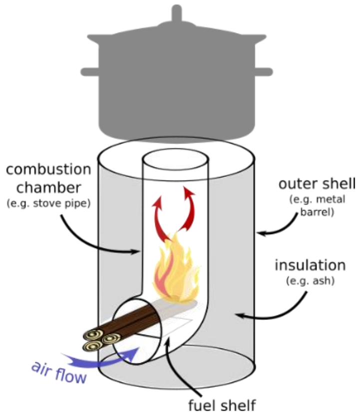

Figure 7. Rocket stove parts. Source: Wikipedia, 2021.

The Clean Cooking Alliance Catalog (CCA, 2021) has compiled the stove performance and consumption of near 500 models and more than 770 test results.

2.1.2 Clean cooking

SDG target 7.1 calls for ensuring universal access to "affordable, reliable and modern energy services", but the **UN global indicator** for this target is the proportion of population with "**primary reliance on clean fuels and technology**", and consequently the annual progress report to track the advance measures this indicator.

The choice of this indicator is due to the fact that it has already been collected for some time. Household Energy Database (WHO, 2018) collects information from more than 1000 surveys in more than 150 countries.

Emissions

In accordance with WHO (WHO, 2014), there are several combustion pollutants with risk for health, such as PM2.5, PM10, Benzene, CO, Formaldehyde, Naphthalene, Nitrogen dioxide, and Polycyclic-aromatic hydrocarbons. However, PM2.5 and CO together serve as sufficient indicators of the health damaging potential of household fuel combustion in most situations. Therefore, WHO has set only guidelines for these two pollutants, setting their maximum levels of exposure to avoid health damage.

The relative risk of many illnesses increases sharply with the exposure concentration (Figure 8).

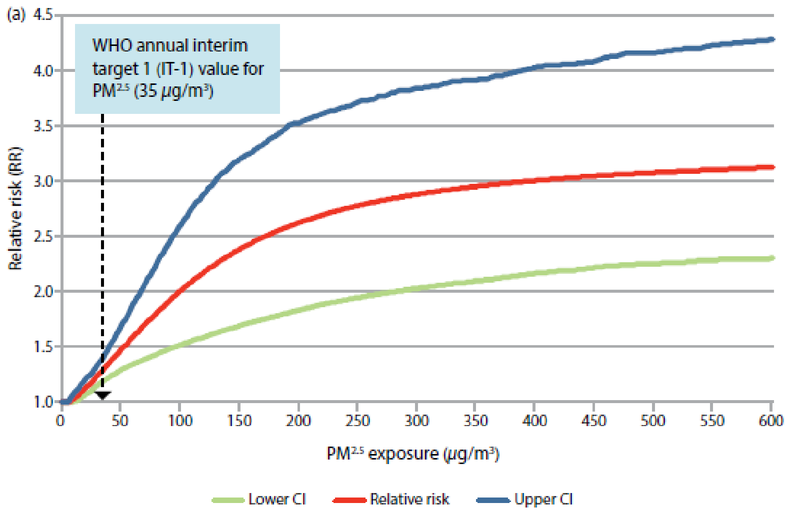

Figure 8 : The relationship between level of PM2.5 exposure and relative risk of children ALRI. Source: WHO, 2014.

To prevent adverse health impacts, the average annual PM2.5 concentration should be lower than 10 µg/m^3, and the 24-hour exposure to CO concentration should be less than 7 mg/m^3 (WHO, 2014). These levels are known as WHO Air Quality Guidelines (WHO AQG). For contexts in which meeting these levels may be unrealistic in the short term, WHO established the interim air quality targets for PM2.5 concentration, it not being necessary to do so for the CO concentration. The WHO Interim Targets (WHO IT) for annual mean PM2.5 are:

- IT-1: 35 µg/m^3.
- IT-2: 25 µg/m^3.
- IT-3: 15 µg/m^3.
- AQG: 10 µg/m^3.

WHO has developed a model to link the indoor air pollutant concentration, measured in µg/m^3 or mg/m^3, with the emission rate of a cookstove, measured in µg/min or mg/min (WHO, 2014). With several assumptions on ventilation, air exchange rates, kitchen volumes, and devices burn time, WHO concluded that emission rates should not exceed the following values:

- PM2.5 (unvented): 0.23 mg/min.
- PM2.5 (vented): 0.80 mg/min.
- CO (unvented): 0.16 g/min.
- CO (vented): 0.59 g/min.

The ISO/TR 19867-3:2018 Voluntary Performance Targets (VPTs) measure the emissions not in µg/min or mg/min but in mg/MJ delivered and g/MJd.

(ESMAP, 2020b) defines clean cooking solutions as "Fuel-stove combinations that achieve emissions performance measurements of Tier 4 or higher following ISO/TR

19867-3:2018 Voluntary Performance Targets (VPTs), which refer to the World Health Organization's 2014 guidelines for indoor air quality".

Clean fuels

WHO's Household Energy Database (WHO, 2018) considers 10 fuels: biogas, charcoal, coal, crop residues, dung, electricity, kerosene, liquid petroleum gas (LPG), natural gas and wood. There may be other traditional fuels such as alcohol/ethanol, processed biomass (pellets), woodchips, garbage/plastic, or sawdust (WHO's Catalogue of Cooking, Heating and Lighting Fuels and Technologies, 2016), and new marketing formats, such as bottle biogas (Black et al., 2021) and bioLPG (Chen et al., 2021). It is common to make more operational classification, for example, unprocessed biomass (wood and charcoal), processed biomass (pellets and briquettes), liquid fuels, gas fuels and electricity (Development Bank of Rwanda et al., 2021).

Biomass fuels are generally sourced in domestic markets. Natural gas and LPG must be imported in countries that do not have domestic oil and gas resources. Although there are regional electricity markets, most electricity is generated domestically, although technology and sometimes fuels are imported.

ESMAP, WHO and IEA link clean cooking to the use of certain fuels. ESMAP's definition of clean cooking solution is based on the concept of "fuel-stove combination", and WHO considers biogas, ethanol, LPG, natural gas and electricity to be clean fuels. In the first case, electricity, which is a clean cooking solution but not a fuel, and electrical appliances other than stoves, are discarded. In the second case, electricity is incorrectly considered as fuel.

Electricity is always clean because it produces no indoor emissions. Gas is only a "relatively clean-burning fuel" because it has difficulties in meeting the PM2.5 10 $\mu g/m^3$ guideline and its combustion produces emissions of nitrogen oxides, which have been linked to asthma and wheeze (WHO, 2014). There are other clean energy sources, e.g. the solar irradiation used in solar cook stoves, but they are rarely used.

Unprocessed coal and kerosene raise concerns regarding emissions and safety; therefore, they are not considered clean fuels and their use is discouraged (WHO, 2014).

Regarding biomass, stoves without a fume exhaust system have very high indoor emissions; even stoves with a chimney have high emissions because of fugitive fumes. In 2014, WHO did not find any ICS with solid fuel that met WHO IT-1. A few types of vented stoves reached levels close to the range of PM2.5 40–60 μg/m3. In the Clean Cooking Catalog (CCA, 2021a), there are a few models that meet Tier 4 of the ISO/TR norm, for example the Mimi Moto forced air gasifier. However, more recent studies have demonstrated that there are some models that can meet WHO IT-1, for example, Patsari plancha-type chimney stove (Medina et al., 2019). Figure 9 highlights the typical CO and PM2.5 emissions of some cookstove models.

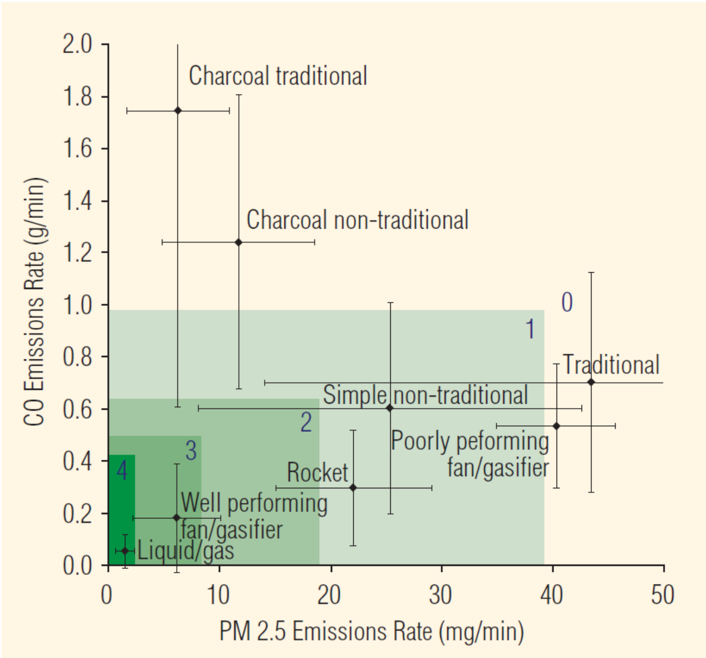

Figure 9. CO and PM2.5 emission rates by stove. Source: Putti et al., 2015.

Smith & Sagar (Smith & Sagar, 2014) argued that there are two basic strategies for achieving clean cooking: "Making available clean", this is using readily available biomass with cookstoves that avoid emissions, and "Making the clean available", this is making clean fuels and electricity affordable for all. However, the same authors point out that after 50 years of promoting supposedly clean cookstoves, they have not noted a demonstrable impact on the national health burden for three main reasons: it is very difficult to cleanly burn fuels that have high variability; the most advanced models do not meet local needs; for cookstoves to have a health impact, emissions must be extremely low. Therefore, it is difficult to advance in the "Making available clean" strategy and the only real option is to promote "Making the clean available".

For these reasons, the IEA in its clean cooking access database excludes biomass fuels, as well as coal and kerosene. The IEA and UN clean cooking accounting systems only consider "primary fuel", which does not guarantee that secondary fuels are clean and meet the WHO AQG. A more adequate accounting should take into consideration all fuels.

Figure 10 shows the utilization of the main fuels in LMIC.

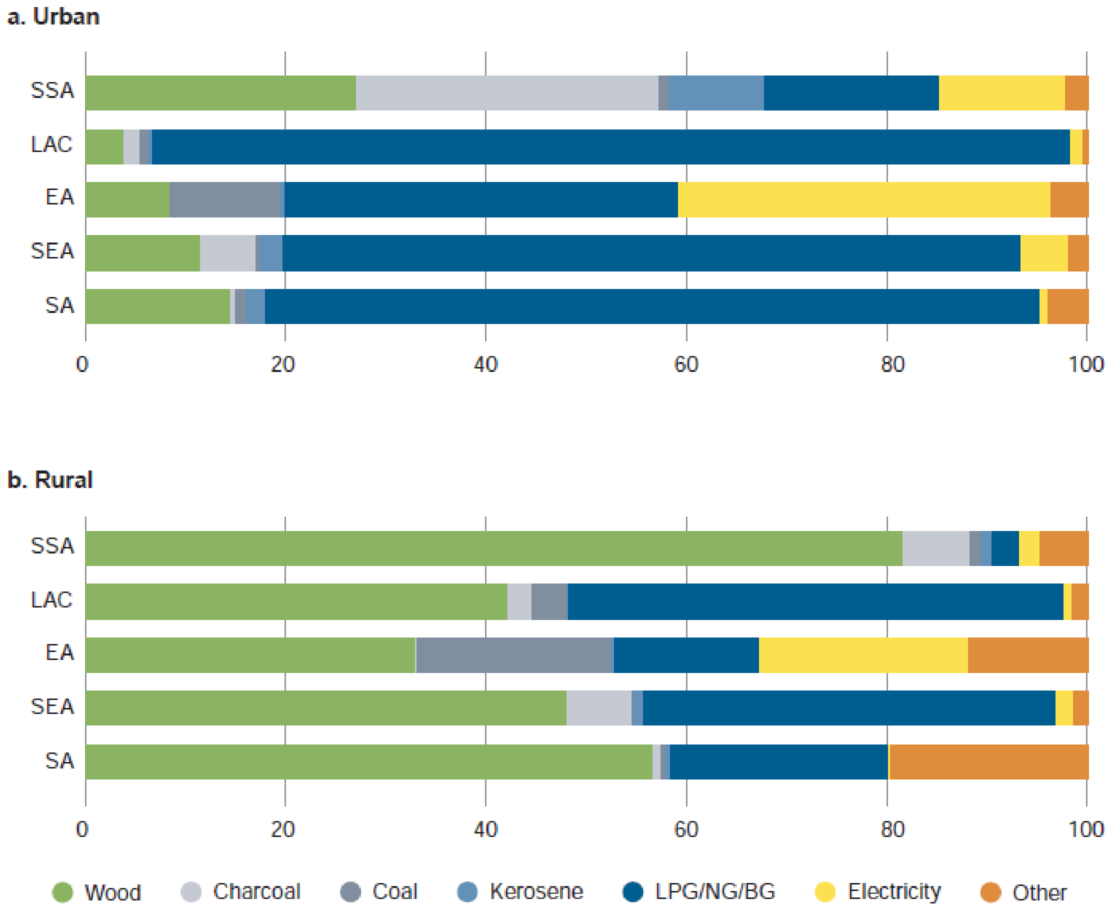

Figure 10.Primary fuel consumption for cooking in Sub-Saharan Africa (SSA), Latin America and Caribbean (LAC), East Asia (EA), Southeast Asia (SEA) and South Asia (SA), in urban (a) and rural (b) areas. Sources: ESMAP, 2020b.

2.1.3 Modern energy cooking services

The Energy Sector Management Assistance Program (ESMAP) established in 2015 the Multi-Tier Framework (MTF) initiative to measure energy access in a levelled approach, from Tier 0 (no access) up to Tier 5 (the highest level of access). The attributes that measure the different dimensions of the access have been modified from the first version (Bhatia & Angelou, 2015) to the new one (ESMAP, 2020b), shown in Table 2. For example, the fuel quality attribute, which refers to its caloric value, moisture, and combustion characteristics, or voltage for electricity-based solutions, is not present in the new version, and the way of measuring safety has changed.

Table 2. Multi-Tier Framework for measuring access to cooking solutions. Source: ESMAP, 2020b.

Attribute	Measurement indicators	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Exposure*	Default ventilation PM2.5 (mg/MJd)	> 1030	≤ 1030	≤ 481	≤ 218	≤ 62	≤ 5
	Default ventilation CO (g/MJd)	> 18.3	≤ 18.3	≤ 11.5	≤ 7.2	≤ 4.4	≤ 3.0
	High ventilation PM2.5 (mg/MJd)	> 1489	≤ 1489	≤ 733	≤ 321	≤ 92	≤ 7
	High ventilation CO (g/MJd)	> 26.9	≤ 26.9	≤ 16.0	≤ 10.3	≤ 6.2	≤ 4.4

	Low ventilation PM2.5 (mg/MJd)	> 550	≤ 550	≤ 252	≤ 115	≤32	≤ 2
	Low ventilation CO (g/MJd)	> 9.9	≤ 9.9	≤ 5.5	≤ 3.7	≤ 2.2	≤ 1.4
Efficiency	Stove efficiency, using ISO's voluntary performance targets (%)	<10	≥ 10	≥ 20	≥ 30	≥ 40	≥ 50
Conveniency	Fuel acquisition and preparation time (hours/week)	≥ 7	≥ 7	≥ 7	10	< 5	< 2
	Stove preparation time (minutes/meal)	≥ 10	≥ 10	≥ 10	<10	< 5	< 2
Safety	Severity of accidents caused by the stove over the past year	Serious	Serious	Serious	Minor	None	None
Affordability	Fuel cost as a share of household expenditure (%)	≥ 10	≥ 10	≥ 10	< 10	< 5	< 5
Availability	Ready availability of primary fuel when needed (% of the year)	≤ 80	≤ 80	≤ 80	> 80	> 90	100

* ISO's voluntary performance targets on emissions.

The exposure and efficiency tiers depend not only on the stove but also on fuel-stove combination. For example, an efficient cookstove can perform badly and emit high emissions if the fuel is of poor quality.

MTF provides a better system of indicators to track SDG 7.1.2, ensuring universal access to affordable, reliable, and modern energy services.

- An affordable energy service is measured by the MTF affordability attribute.
- A reliable energy service is measured by the MTF fuel availability attribute.
- A modern energy service is measured by cooking exposure, cookstove efficiency, convenience, and safety attributes.

ESMAP is promoting the implementation of MTF Energy Access Country Diagnostic Reports. Since the initiative was launched, 16 diagnostics have been carried out: Bangladesh, Cambodia, Democratic Republic of Congo, Ethiopia, Honduras, Kenya, Liberia, Madagascar, Myanmar, Nepal, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Zambia, and Uganda. Further rollout is planned for Burkina Faso, Burundi, Cameroon, Malawi, Sierra Leone, and Zimbabwe. By November 2020, another 6 were in progress (ESMAP, 2020b).

Based on MTF, ESMAP defines two new concepts:

- **Modern Energy Cooking Services (MECS)**: When a household context meets the standards of Tier 4 or higher across all six attributes.
- **Improved cooking services**: When a household context meets at least Tier 2 standards of the MTF across all six attributes, but not all of Tier 4 or higher. Household contexts with a status of MTF Tier 2 or Tier 3 are considered in transition.

ESMAP has published its first report on the State of Access to Modern Energy Cooking Services using these new concepts. Whereas the UN's clean cookstove measurement only refers to the exposure attribute, MECS refers to the six MTF attributes. In 2019 it was estimated that 2.6 billion people were without clean cookstoves but 4 billion were without MECS (ESMAP, 2020b; IEA et al., 2021).

2.1.4 Cooking space

Concentration of pollutants depends on the fuel-stove combination, the cooking space and ventilation.

WHO (2016, 37) established five basic locations for the stoves or cooking areas:

- Inside the main house in no separate room.
- Inside the main house in a separate room.
- Outside the main house in a separate room.
- On a veranda/covered porch.
- Outdoors/open air.

Many households in LMIC cook either indoors, or outdoors in a separate building, particularly in rural areas (Figure 11), and Africa has 18 out of 20 countries that cook most outdoors (Langbein et al., 2017).

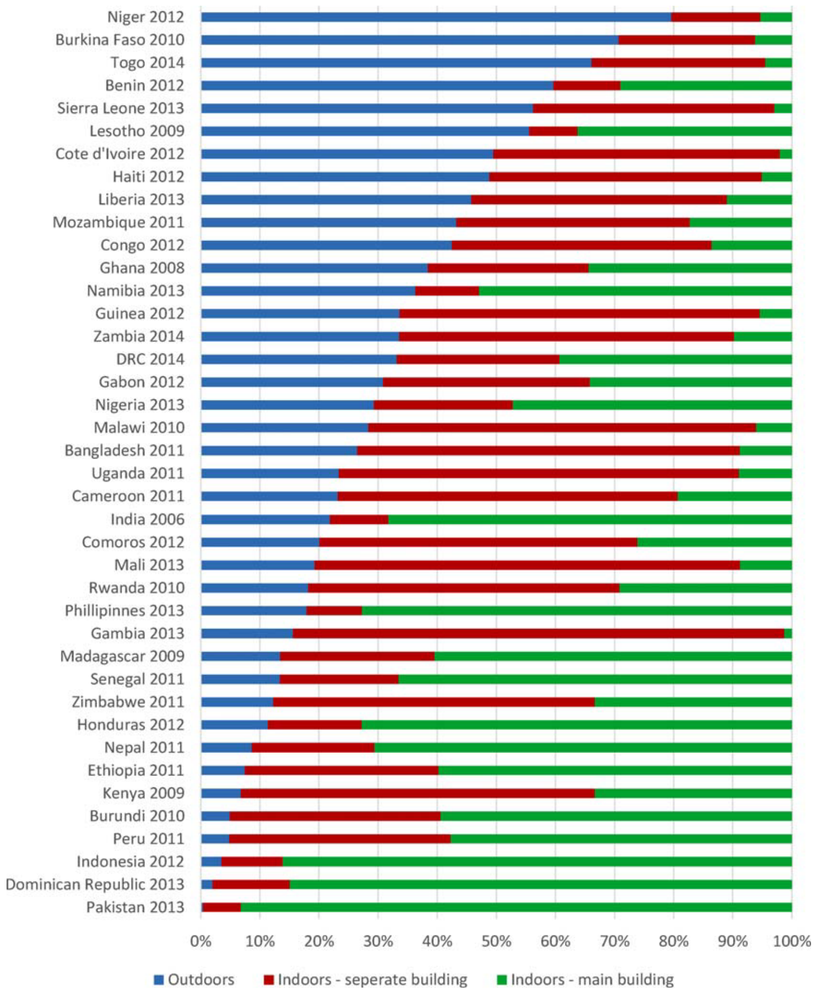

Figure 11. Cooking location in rural areas in developing countries. Source: (angbein et al., 2017.

When cooking indoors, ventilation depends on the kitchen configuration (Olaya, 2017):

- Location in the household.
- Design.
- Size.
- Materials.
- Orientation.
- Air circulation (chimney, hood, windows, cross ventilation).
- Stove location.

A field study in 22 households in Senegal (de la Sota, 2017) demonstrated that thatched roofs led to lower HAP levels, when compared to homes with metal roofs. Higher values of the free area of inlet/outlet opening (e.g., the sum of areas of windows, doors and other outlets in the kitchen) also contributed to a reduction of indoor air pollution. Finally, although to a lesser extent, kitchen volume was also found to affect indoor concentration pollutant levels.

Non-cooking services in the cooking space

The cooking space also requires energy services other than cooking, and it may be interesting to situate cooking interventions in a broader framework that includes:

- Lighting: both natural and artificial, general and task-specific.
- Food preservation and preparation: especially for refrigerators and small electrical appliances.
- Ventilation and temperature: especially for the use of fans or mechanical smoke extraction systems.
- Water: essential for cooking meals and washing kitchen utensils; also essential for hygiene, washing clothes and cleaning the house.
- Hot water: used especially for hygiene and cleaning.

Non-cooking services met by fire

Fire used for cooking may have complementary functions, such as waterproofing thatched roofs, repelling insects, lighting, heating, or functions related to gathering and spirituality (Ruiz-Mercado & Masera, 2015). If the fire is replaced with a new cooking system, it is necessary to continue to cover these functions, for example, by replacing thatched roofs with waterproof ones, or by providing an alternative heating system.

2.1.5 Measuring cooking solutions performance

There are two basic ways of measuring the performance of cooking systems: laboratory tests and experimental studies (randomized and non-randomized). Laboratory tests give useful information to select the best stoves but are far from representing the real situation of the stoves' performance when they are used as real cookers in households, as they use a simplification of what is actually cooked, cooking more carefully and not capturing the different cooking styles. Experimental studies give better results but are more expensive.

Over the last twenty years, different measurement protocols have been developed, such as the Controlled Cooking Test (CCT) (Bailis et al., 2004), the Kitchen- Performance Test (KPT) (Bailis & Edwards, 2018) or the Water Boiling Test (WBT) (Bailis et al., 2007).

ISO first developed an International Workshop Agreement, the ISO/IWA 11:2012 Guidelines for evaluating cookstove performance (ISO, 2012), which subsequently evolved into a family of standards:

- ISO 19867-1:2018. Clean cookstoves and clean cooking solutions. Harmonized laboratory test protocols. Standard test sequence for emissions and performance, safety and durability.
- ISO/TR 19867-3:2018. Clean cookstoves and clean cooking solutions. Harmonized laboratory test protocols. Voluntary performance targets for cookstoves based on laboratory testing.
- ISO 19869:2019. Clean cookstoves and clean cooking solutions. Field testing methods for cookstoves.
- ISO/TR 21276:2018. Clean cookstoves and clean cooking solutions. Vocabulary

Table 3 shows the ISO/TR voluntary performance targets for thermal efficiency, emissions, safety and durability.

Table 3. ISO/TR voluntary performance targets. Default values. Source: ISO, 2018.

Tier	Thermal efficiency %	Emissions		Safety (score)[b]	Durability (score)[c]
		CO (g/MJd[a])	PM2.5 (mg/MJd[a])		
5	≥50	≤3.0	≤5	≥95	<10
4	≥40	≤4.4	≤62	≥86	<15
3	≥30	≤7.2	≤218	≥77	<20
2	≥20	≤11.5	≤481	≥68	<25
1	≥10	≤18.3	≤1030	≥60	<35
0	<10	>18.3	>1030	<60	>35

[a] MJd: Megajoule delivered. [b] Safety protocols (ISO 19867-12018, Clause 7). [C] Durability protocols (ISO 19867-12018, Clause 8).

Although ISO standards are currently the international reference, many of the available measurements are made with previous ISO/IWA 11:2012, such as those of the models available in the Clean Cooking Alliance Catalog (CCA, 2021a).

In order to measure emissions in laboratories, the Aprovecho Research Centre has developed the Laboratory Emissions Monitoring System (LEMS), which is widely used (Figure 12). In addition, there is a network of more than 40 Regional Testing and Knowledge Centers (RTKC) which measure, and in some cases assure the cookstove performance. Portable Emission Monitoring Systems (PEMS), designed by the Aprovecho Research Centre, may be used for field work.

Figure 12. Laboratory Emissions Monitoring System (LEMS). Source: Aprovecho, 2021.

When the relationship between CO and PM2.5 concentration is known, PM2.5 concentrations can be used as a proxy for CO, making the measurement much cheaper and affordable in many projects. To track PM2.5 build-ups, there are portable data logging devices, such as the PATS, developed by the Berkeley Air Monitoring Group (Berkeley Air Monitoring Group, 2021). There are also several low-cost models; however, as yet they are not completely reliable (Curto et al., 2018).

In order to assess the black carbon concentrations, there are again low-cost methods, like reflectometry and camera-based systems, while the use of smartphones with cameras opens up new possibilities for measuring (de la Sota, 2017).

Energy consumption

Beyond knowing the efficiency and the emission rate, it is necessary to know the energy consumption to estimate other variables, such as total emissions, biomass consumption, or cooking costs.

The household energy consumption for cooking varies with the number of people per household, the type of food, the number of food types included in a particular meal, the cooking style, etc., and a large difference is found in the literature, ranging from 0.36 MJ/capita/meal to 6 MJ/capita/meal (Dagnachew et al., 2020). The most accurate measurement of energy consumption comes from field studies.

In the absence of such studies, a theoretical approximation can be used based on final energy demanded, the energy efficiency of the stoves and the calorific values of the fuels, according to equation X:

$$Fuel\ consumption\ (Kg) = \frac{Final\ energy\ (MJ)}{Energy\ Efficiency * Fuel\ calorific\ values\ \left(\frac{MJ}{Kg}\right)} \qquad [X]$$

Typical values for final energy are:

- 1 GJ/capita/year (Jacobs et al. 2026).
- 3 MJ/capita/day (Dagnachev et al., 2020).
- 3.64 MJ/standard meal (IEA, 2017).

When using the standard meal, 2.5 standard meals per day can be considered.

The default calorific values are shown in Table 4:

Table 4. Default calorific values for main cooking fuels. Source: IPCC, 2006.

Fuel	Calorific value MJ/kg
Wood	15.6
Charcoal	29.5
LPG	47.3
Natural gas	48.0

In order to ascertain the consumption of a region, the use of each technology and number of households can be taken from National Surveys or MTF Surveys.

This method allows us to know the daily consumption, but not its distribution over time, which is important for eCooking. To know the time distribution, thermal sensors with a data logger like the one promoted by the Berkeley Air Monitoring Group, or electricity meters, can be used.

Where such measuring equipment is not available, or where supplementary information is needed, a log of cooking tasks should be used. A Cooking Diaries methodology has been developed by Leary (Leary, Batchelor, et al., 2019) and applied in four countries Kenya, Tanzania, Zambia and Myanmar (Leary, Scott, et al., 2019).

2.2 Electric Cooking (eCooking)

2.2.1 eCooking appliances

The most popular technologies for cooking are hobs. These appliances are not particularly energy efficient; nevertheless, they are inexpensive and well known. Induction cookstoves are safe, non-polluting, highly efficient, and have been identified as a potential “leapfrog technology” because of their energy efficiency and safety (Banerjee et al., 2016; Smith & Sagar, 2014), and there have been several attempts to promote induction stoves to replace fuel stoves. However, these initiatives have not had the expected results due to the necessity of replacing old cooking utensils with new ferromagnetic ones, which increase costs and reduce acceptance. However, in some countries such as India, inexpensive induction stoves are becoming increasingly popular for regular cooking (WHO, 2014).

The most efficient appliances are microwave ovens and insulated appliances, such as rice cookers, insulated electric frying pans, thermo pots and electric pressure cookers (EPS). EPS can also be considered a “leapfrog technology”. The best in-class models are able to heat the ingredients and maintain the pressure during 30 minutes with less than 200 Wh for 2.5 litres and 450 Wh for 6 litres (Global LEAP Awards, 2021), and an EPS allows the cooking of up to 90% of the dishes of a typical menu in most countries (ESMAP, 2020a), with a consumption of between 0.1 and 0.7 kWh for the typical dishes (Scott & Coley, 2021). Leary (Leary, 2018) has described the main features of the EPC.

Table 5 shows the main electric cooking appliances characterized by their energy efficiency, heat transfer in and out of pot, typical power requirements, speed, and versatility. In most countries with a hot plate or induction stove, all meals can be prepared. A combination of two or three appliances may be used, for example: a hot plate and/or an induction stove, and/or a rice cooker, and/or an EPC. Some appliances enable cooking the same meals; for example, food prepared with a rice cooker can also be cooked with an EPC. In some countries, more specialized devices may be required, such as pancake makers in China, roti makers in India (Smith & Sagar, 2014) and injera makers in Ethiopia (Alem et al., 2013).

Table 5. Characterization of the main eCooking appliances. Source: Adapted from ESMAP, 2020a.

Appliance	Heat transfer into pot	Heat transfer out of pot	Typical power require-ments	Speed	Versatility
Inefficient conventional appliances					
Hot plate	Conduction when pot in contact with element	Convection and radiation from uninsulated pot; evaporation without lid	1–2kW per hob (DC: 300–700W)	Average	Any pot (round bottom difficult); frying and boiling
Electric oven	Convection	Cooking chamber insulated, but not sealed; whole oven space around pot/dish heated	1–5kW	Slow	Baking, roasting, grilling only
More efficient modern appliances					
Kettle	Conduction via immersed element	Convection and radiation from uninsulated pot; fixed lid, but not completely sealed	1.5–2.5kW	Fast	Single vessel; water boiling only
Slow cooker	Conduction via insulated element	Insulation and fixed lid, but not completely sealed	100–200W	Very slow	Single deep pot; simmering only
Electric frying pan	Conduction via element stuck to pan	Convection and radiation from uninsulated pot; evaporation without lid	1–2kW	Average	Single shallow pot only; frying and boiling
Induction stove	Induction	Convection and radiation from uninsulated pot; evaporation without lid	1–2kW per hob	Fast frying and bringing to boil	Any flat-bottomed ferrous pot; frying and boiling

Infra-red stove	Radiation	Convection and radiation from uninsulated pot; evaporation without lid	1–2kW per hob	Fast frying and bringing to boil	Any flat-bottomed pot; frying and boiling
Halogen oven	Radiation	Convection and radiation from uninsulated chamber; lid, but not completely sealed	700W–1.5kW	Average	Baking, roasting, grilling only
Most efficient modern appliances					
Rice cooker	Conduction via insulated element	Insulation and fixed lid, but not completely sealed	300W–1kW (DC: 200–400W)	Average	Single deep pot only; boiling and some frying,
Microwave	Microwave	Cooking chamber insulated, but not sealed	700W–1.5kW	Fast	Any non-metallic dish; boiling
Insulated electric frying pan	Conduction via insulated element stuck to pan	Insulation; evaporation without lid	700W–1.5kW	Fast frying and bringing to boil	Single shallow pot only; frying and boiling
Thermo pot	Conduction via immersed element	Insulation and fixed lid, but not completely sealed	500W–1.5kW (DC: 200–400W)	Slow	Single vessel; water boiling only
Electric pressure cooker	Conduction via immersed element	Insulation and fixed lid; completely sealed	700W–1.2kW (DC: 200–400W)	Very fast (pressurized) boiling	Single deep pot only; boiling and some frying

eCooking appliances can incorporate different functionalities (precise power control, timer, pot presence sensor switching off, lock and child lock, pause, automatic switch off, temperature limitation). In these cases, the appliances are called "smart" to differentiate them from the "standard" ones.

2.2.2 Electricity for eCooking

(Bhatia & Angelou, 2015) defines energy access as "the ability of the end user to utilize energy supply that is usable for the desired energy services". Use of appliances is inherent to energy access and is a crucial element to consider. Energy access can be defined either inclusive or exclusive of use of appliances. When defined exclusive of appliances, it is called access to energy supply, and when defined inclusive of appliances, it is called access to energy services. Energy services encompass lighting, cooking, air circulation, refrigeration, air conditioning, heating, communication, entertainment, computation, motive power, etc.

In many settings in LMIC, the lack of access can be related to both the lack of energy source (carriers) and the lack of appliances. Moreover, these two factors influence each other. When a household has little equipment, its energy demand is low, and when the energy supply is not reliable or affordable, there is no interest in buying more equipment. For this reason, in many cases, it is necessary to consider the pair energy source-appliance. What is more, efficient appliances reduce electricity demand.

Until a few years ago, the main option for electricity supply had been grids, but microgrids and isolated systems are becoming increasingly important. According to (ESMAP, 2019), by 2030, half a billion people will have electricity supply from microgrids[1]. In areas that do not yet have electricity supply, the most economical mode of development depends to a large extent on demand. For already connected users, the increased demand for eCooking will lead to the need to increase generation capacity. The electricity supply will have to guarantee both the non-cooking demand and the cooking demand.

Non-cooking electricity demand

The International Energy Agency considers that a household has access to electricity if it is able “to power four lightbulbs operating at five hours per day, one refrigerator, a fan operating 6 hours per day, a mobile phone charger and a television operating 4 hours per day” (IEA, 2020a). The IEA estimates that 1,250 kWh/HH/year is sufficient to meet these services with standard appliances, and 420 kWh with efficient ones, although with high efficiency appliances, the latter figure can be much lower. ESMAP considers 1 kWh/day/HH as “basic consumption package” to estimate the affordability of electricity.

To track the household electricity access, there is also a Multi-Tier Framework (MTF) with seven attributes (Table 6).

Table 6. Multi-Tier Framework for Measuring Access to electricity. Source: ESMAP, 2020.

Attribute	Measurement indicators	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Capacity	Power capacity ratings (W or daily Wh)	Less than 3 W	At least 3 W	At least 50 W	At least 200 W	At least 800 W	At least 2 kW
		Less than 12 Wh	At least 12 Wh	At least 200 Wh	At least 1 kWh	At least 3.4 kWh	At least 8.2 kWh
	Services	Lighting of 1,000 lmhr per day	Electrical lighting, air circulation, television, and phone charging are possible				
Availability	Daily Availability	Less than 4 hours	At least 4 hours		At least 8 hours	At least 16 hours	At least 23 hours
	Evening Availability	Less than 1 hour	At least 1 hour	At least 2 hours	At least 3 hours	At least 4 hours	

[1] The difference between microgrids and mini grids would be the size of the network, but there is no established criterion of where the barrier between the two is. In this document the term microgrid will be commonly used to refer to isolated networks of any size.

Reliability		More than 14 disruptions per week	At most 14 disruptions per week or at most 3 disruptions per week with total duration of more than 2 hours	(> 3 to 14 disruptions / week) or 3 disruptions / week with > 2 hours of outage	At most 3 disruptions per week with a total duration of less than 2 hours
Quality		Household experiences voltage problems that damage appliances		Voltage problems do not affect the use of desired appliances	
Affordability		Cost of a standard consumption package of 365 kWh per year is more than 5% of household income	Cost of a standard consumption package of 365 kWh per year is less than 5% of household income		
Formality		No bill payments made for the use of electricity		Bill is paid to the utility, prepaid card seller, or authorized representative	
Health and Safety		Serious or fatal accidents due to electricity connection		Absence of past accidents	

Reliability is typically measured by a combination of two indexes that are strongly correlated: frequency of outages using the System Average Interruption Frequency Index (SAIFI), and duration of outages using the System Average Interruption Duration Index (SAIDI). In general, interruptions are more frequent in rural areas, both because they are more likely to be disconnected when the supply cannot meet demand and because of lower maintenance of distribution grids.

In LMIC, consumption in rural areas is lower than in urban areas. When a household is connected to the mains, its initial consumption is low because it has few electrical appliances. Over time, consumption increases to stabilize after a few years. A study conducted in Kenya with 136,000 new users showed that rural consumers consume 50% less than urban and peri-urban consumers, and that new users reach steady-state consumption faster and faster, stabilizing at around 20 kWh per month (Fobi et al., 2018).

Cooking demand

Electricity consumption of eCooking varies depending on the appliances used, the type of food cooked or the cooking practices. Empirical data recorded by 80 households in Kenya, Myanmar, Tanzania and Zambia shows that using a mixture of conventional and energy-efficient appliances, the average daily consumption is 0.88–2.06 kWh, for a 4.2 person household (ESMAP, 2020a). The electricity demand is concentrated between 4 a.m. and 11 p.m., with some peaks associated with breakfast, lunch and dinner (Figure 13).

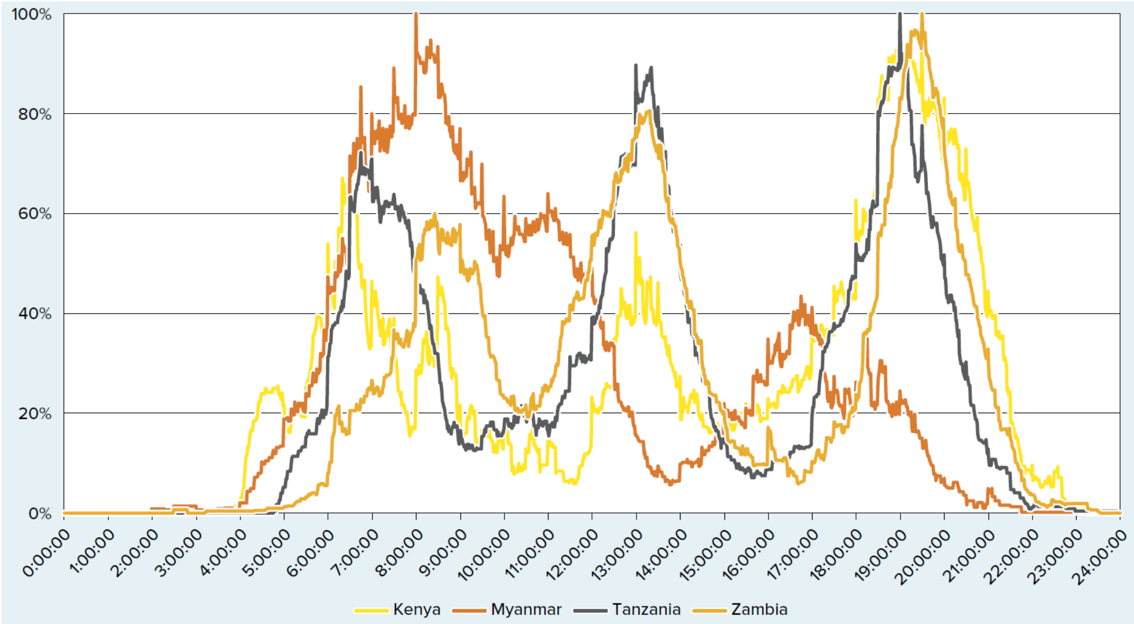

Figure 13. Normalized 24-hour load profile aggregated in Myanmar, Kenya, Tanzania and Zambia. Source: ESMAP, 2020.

In countries with low electricity consumption in households, eCooking drastically changes electricity consumption (Banerjee et al., 2016), quite the opposite of what happens in countries with high consumption; for example, in South Korea, the transition to eCooking with an induction stove would only mean an 11.7% increase in household consumption (Kim et al., 2017).

The introduction of eCooking in microgrids has specific characteristics, and there are recent studies that examine this topic (Bilich et al., 2021; ESMAP, 2020a; Keddar et al., 2021; Lombardi et al., 2019, 2019).

2.3 Cooking impacts

Cooking directly impacts several of the SDGs (Mazorra et al., 2020):

- SDG 3 – Good health and well-being: due to air pollution
- SDG 5 – Gender equality: since it is the women who usually take care of the cooking tasks.
- SDG 13 – Climate Action: due to climate pollutants.

In addition, it may affect other SDGs more indirectly (Olaya, 2017): SDG 1 – No poverty, due to economic expenditure on fuels; SDG 2 – No hunger, because a cooking system is needed to prepare food for people affected by malnutrition; SDG 4 – Quality education, since in many cases it is the children who are dedicated to collecting firewood and cooking, taking time away from their education; SDG 8 – Decent work and economic growth, since the sectors of production and distribution of fuels, electricity, stoves and cooking appliances are sources of employment and economic activity; SDG 9 – Industry, innovation and infrastructure, since the supply of energy for cooking requires infrastructure and an industry, and there is an important space for innovation; SDG 11

– Sustainable cities and communities, for the living conditions of households; SDG 12 – Responsible consumption and production, because the choice of cooking systems depends in part on purchasing conditions, and on compliance with production standards, and SDG 15 – Life on land, due to the problems of unsustainable biomass collected for cooking and deforestation.

The following subsections analyse the main impacts of cooking.

2.3.1 Health

The most important health problems are those associated with HAP. For young children under 5 years old, they include acute lower respiratory infections (ALRI), low birthweight, stillbirth, and stunting, while for adults, chronic obstructive pulmonary disease (COPD), lung cancer and cardiovascular disease. Less frequent problems for children under 5 years old can include mortality, cognitive development problems and asthma, and for adults, cataracts, other types of cancer and also asthma (WHO, 2014). There are other health risks not related to air quality, such as burns, scalds, poisoning from ingestion of liquid fuel, poisoning from gas leakage, house fires or gas explosions.

The reduction of personal exposure to pollutants is the main aspect in improving the health impact of clean cooking systems. (WHO, 2014) developed a causal chain relating household energy technology, fuel and other interventions to health and safety outcomes via intermediate links. Based on this casual chain concept, Figure 14 shows other factors contributing to health impacts.

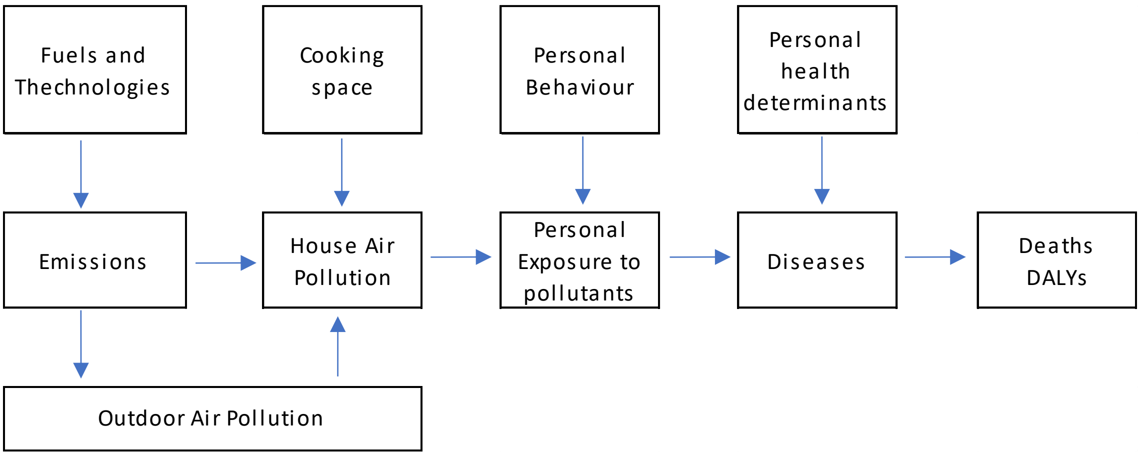

Figure 14. Health impacts causal chain. Source: own elaboration.

Health determinants that have not been previously addressed are discussed below.

<u>Outdoor emissions</u>

HAP is responsible for 12% of outdoor PM2.5 pollution (Smith & Sagar, 2014). In densely populated areas, cooking emissions worsen outdoor air quality, which on the one hand can re-enter homes and can increase HAP in some households, and on the other hand can affect people outside. Therefore, in terms of public health, it is not enough to reduce indoor emissions through ventilation systems that expel air to the outside, but rather it is important to reduce total emissions.

Personal behaviour

A cooker can reduce emissions, increase ventilation and reduce personal exposure. Several measures that can be taken to reduce emissions are:

- Use dry firewood
- Use small pieces of wood to fit in the combustion chamber
- Clean and maintain properly the stove and the chimney

If non-chimney stoves are used, open air spaces must be prioritized. If this is not possible, windows and doors must remain open, and exhaust systems installed. To reduce exposure, only cookers must be in the cooking space, and they must minimize the time spent close to the stove. Elderly people and children, as well as people with existing respiratory and cardiovascular diseases, should be kept clear of polluted environments.

Assessment health impacts

(Burnett et al., 2014) developed an integrated risk function for estimating the global burden of disease that is commonly used to assess the health impact of cooking interventions. Through an integrated exposure response (IER) function, the relative risk (RR) for the following five diseases was estimated: Lung Cancer; Ischemic Heart Disease (IHD); Stroke; Acute Lower Respiratory Infection (ALRI) in those aged 0-4; and Chronic Obstructive Pulmonary Disease (COPD), depending on PM2.5 concentration values (IHME, 2016). Based on this IER, the IHME calculates every year the HAP-attributable burden for every country (IHME, 2021), and (Pillarisetti et al., 2016) have developed the online Household Air Pollution Intervention Tool (HAPIT) (CCA, 2016) to estimate the averted disability-adjusted life years (DALYs) and deaths for a cooking programme.

One of the main barriers to using the IER or HAPIT is the need to have reliable data on indoor 24-hour PM2.5 concentration, since the wide range of data that appears in the literature does not allow to have good reference (de la Sota, 2017; Medina et al., 2019; Rosenthal et al., 2018; WHO, 2020).

In addition to estimating the health impacts of HAP, in some cases, the contribution of cooking to outdoor Air Pollution and its impacts on the health of the general population is also estimated (Das et al., 2021).

2.3.2 Gender

The lack of access to MECS affects women and men differently due to gender roles in cooking. In the LIMC, the tasks of preparing food are mainly carried out by women, and they therefore receive the associated negative impacts. Women and children are more exposed to HAP, which makes HAP the second largest environmental risk for women, and is the cause of half of the pneumonia deaths in children (de la Sota, 2017). In countries like Rwanda, women are three times more likely to suffer from health problems associated with HAP than men (World Bank, 2018). There is also gender-based violence associated with firewood gathering.

Figure 15 shows that women spend more time cooking than men in all countries analysed, and more time collecting firewood in many of them (ESMAP, 2014; Putti et al., 2015). The time spent collecting firewood can be more than 10 hours a week in some contexts, taking time away from women for productive activities or leisure, exacerbating the problem called "time poverty" (Mazorra et al., 2020). Time spent cooking and collecting firewood are the most used indicators to measure gender impacts. It is also interesting to measure the time spent cleaning, because although it is less than cooking and collecting firewood, it is not negligible and can change substantially with the introduction of new cooking technologies (Marchand, 2021).

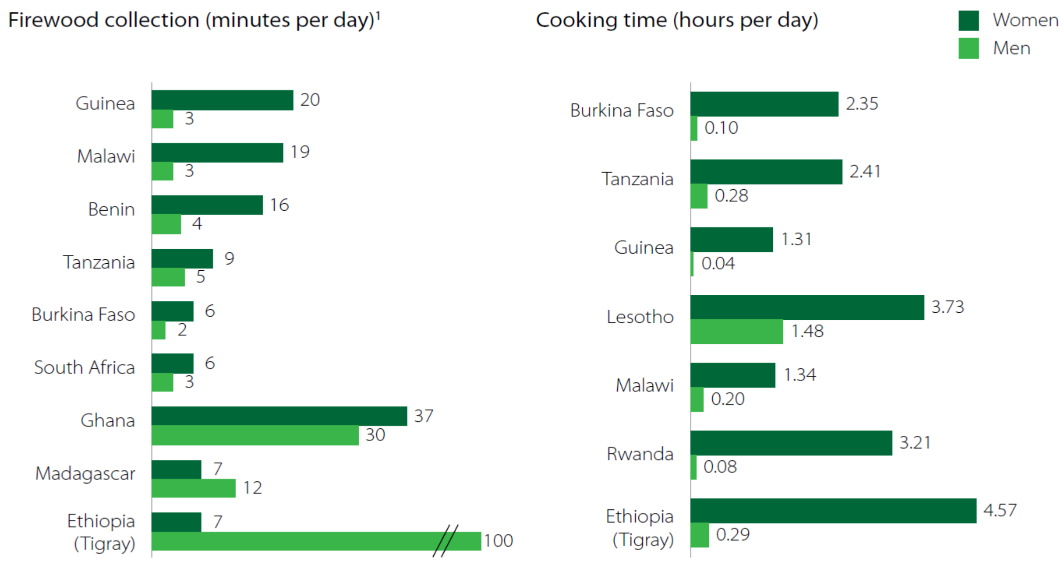

Figure 15. Firewood collection and cooking time, by gender. Source: ESMAP, 2014.

Gender analysis in MTF surveys (World Bank, 2018) found differences between male-headed and female-headed households in areas such as: the use of three-stone stoves, traditional stoves and ICS; willingness to pay for ICS; or the decision to buy a new stove.

On the other hand, income-generating economic activities such as the production, transport and distribution of fuels, work in the electricity sector, or the manufacture of stoves are mostly carried out by men.

2.3.3 Environmental

Life cycle assessment

ERG (2017) conducted life cycle assessments (LCA) of the main fuels and electricity used for cooking in four countries in Africa (Gahan, Kenya, Nigeria and Uganda), three in Asia (China, India and Bangladesh) and one in America (Guatemala). One of the main conclusions is that there are important differences between countries for the same indicator and fuel, with impacts up to ten times greater in some countries than in others. Moreover, as in the case of electricity, none of the three main fuels used in LMIC has low environmental impact in all indicators (Table 7).

Table 7. Environmental impact of main cooking fuel and electricity. Source: Adapted from ERG, 2017.

Indicator	Firewood	Charcoal	LPG	Electricity[1]
Total energy demand	Medium	High	Medium	Medium
Net energy demand	Medium	High	Medium	Medium
Global climate change potential	High	High	Medium	High
Black carbon and short-lived climate pollutants	Medium	High	Low	Low
Particulate matter formation potential	Medium	High	Medium	Medium
Fossil fuel depletion	Low	Low	High	High
Water depletion	Low	Low	High	High
Terrestrial acidification potential	High	Medium	Medium	High
Freshwater eutrophication potential	High	High	Low	Medium
Photochemical oxidant formation potential	High	High	Medium	Medium

[1]Electricity data is only from China and India, with a high percentage of coal in their electricity generation mix.

The impact of biomass depends largely on whether or not it is renewable, which is measured with the non-renewable biomass factor (fNRB) (Equation 1),

$$fNRB = \frac{NRB}{NRB + DRB} \quad (1)$$

where DRB is the demonstrably renewable biomass and NRB is the Non-renewable biomass.

When the fNRB is greater than 50%, it can be considered a "hotspot". The fNFB is calculated from woodfuels Integrated Supply/Demand Overview Mapping (WISDOM) (Drigo et al., 2002; Ghilardi et al., 2016) and is available to many countries (Drigo et al., 2014). (Bailis et al., 2017) have drawn attention to the fact that many of the cooking projects to generate carbon offsets have overestimated the fNRB, and therefore the reductions in CO_2eq will be smaller than those projected.

Charcoal is the combustible that has the greatest environmental impacts. Whereas the use of biomass, coal and kerosene has reduced in recent years in the LMIC, charcoal use has remained approximately unchanged in percentage, around 3% (WB, 2021), which is an increase in absolute terms derived from the increase in the global population (Figure 16). In addition, in the Sub-Saharan cities, charcoal accounts for 29% of consumption (WB, 2021), and there are forecasts that its consumption in rural areas will increase (IEA, 2014).

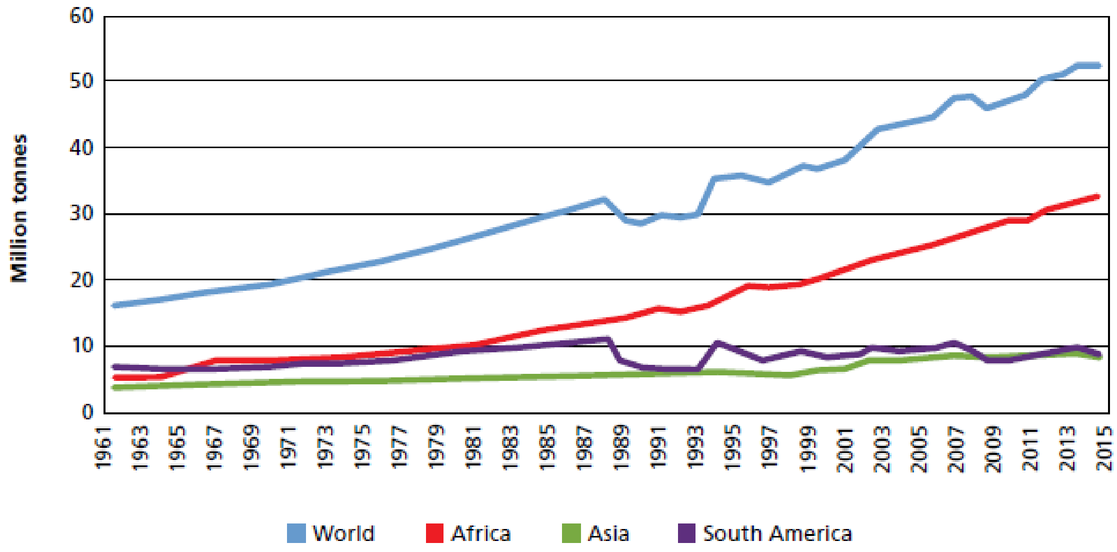

Figure 16. Wood charcoal production worldwide and by region. Source: FAO, 2017.

The environmental impact of charcoal derives both from the renewability of the wood from which it is produced, and from the production method, since in many cases artisanal techniques are used with very low yields and high environmental impacts. There are multiple initiatives to improve the production of charcoal (FAO, 2017).

Natural gas and LPG in many contexts have less environmental impact than firewood, charcoal or electricity generated with a mix based on fossil fuels. However, they are non-renewable resources, and their impacts are not negligible (ERG, 2017), which has led some countries to impose banning their use in future households (Ivanova, 2019).

The environmental impacts of electricity depend to a large extent on how it is generated, and most studies analyse the electricity supplied by the grid. However, recently they have begun to make LCA for microgrids (Leach et al., 2021), highlighting the high impact of some wooden poles used for the distribution grids, or the impact of lithium batteries, which is not as high as that of other components (Lee, 2021).

2.3.4 Climate change

Cooking is not amongst the top sources of global greenhouse gas (GHG) emissions, being responsible for between 1.5-3% of the global amount (Bailis et al., 2017; Putti et al., 2015). Moreover, LMICs are not major per capita emitters (IPCC, 2014, 2015) and have no historical responsibility in the climate crisis because of their low emissions in the past. However, there are several reasons to address the climate impact of cooking:

- In the context of climate crisis, any long-term planning exercise involving large populations must consider emission reduction targets, in line with the Paris Agreement.
- Many of the emissions from cooking are short-lived climate pollutants, whose permanence in the atmosphere is relatively short, so its reduction can make a rapid contribution to the mitigation of GHG.

- There are funding opportunities associated with GHG reduction.
- In the context of increasing GHG emissions in LMIC, reducing emissions from cooking can allow more room for emissions from other sectors, such as agriculture, industry or transport.
- Many of the climate pollutants are also air pollutants, so their reduction also has positive health effects.

Biomass fuels, even if renewably harvested, are not GHG neutral because of their substantial emission of products from incomplete combustion (PIC) (Smith et al., 2000). To be carbon neutral, the biomass must be 100% renewable and the efficiency of combustion would be without PIC that is very difficult to achieve (Smith, 2000). The short-lived climate pollutants (SLCP) from biomass are significant.

Short-lived climate pollutants and carbonaceous aerosol emissions

Black carbon, methane, tropospheric ozone, and hydrofluorocarbons are the SLCP that contribute most to climate change. In the residential and cooking sector, the main SLCP is black carbon (BC). It is estimated that the residential sector is responsible for 2% of global BC emissions (Bond et al., 2013), with significant variation between regions, as shown in Figure 17. Forecasts for 2030 for Asia and Africa are that BC emissions from biomass will be approximately 50% (de la Sota, 2017), and the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC) is promoting several initiatives to catalyse rapid reductions.

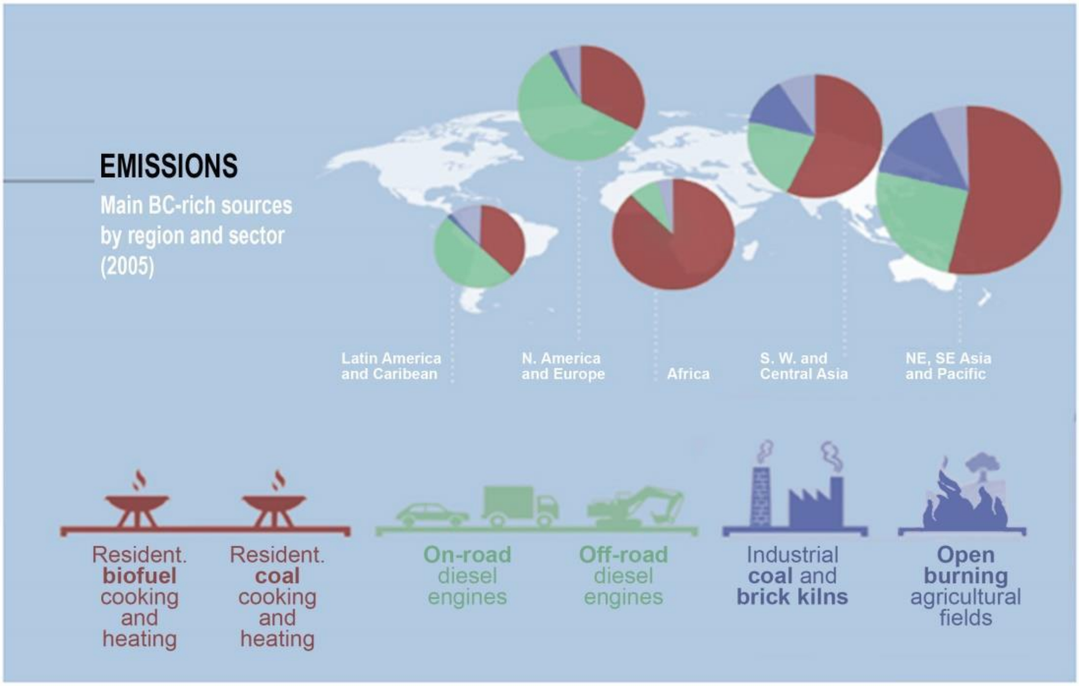

Figure 17. Main BC sources by region and sector (2005). Source: de la Sota, 2017) adapted from CCAC, 2014.

Black carbon (BC), or Elemental Carbon (EC), is a carbonaceous aerosol with days to weeks of lifetime in the atmosphere. Its impacts on the climate are due to both the absorption of solar radiation and reducing the surface albedo when deposited in ice or snow. The variability of BC effects makes the estimation range of its 100-year global warming potential (GWP) very wide, from 120 to 1800, with differences of 30% among regions. Being an SLCF, its effect decreases rapidly when compared to CO2 (Bond et al., 2013).

BC is always emitted with other co-pollutant particles especially organic carbon (OC). OC has usually been considered as a light scattering pollutant with a negative GWP value. However, recent studies have found that it can be a light absorption pollutant because of its association with the brown carbon that absorbs light in ultraviolet wavelengths (Bond et al., 2007; Chung et al., 2012; Feng et al., 2013; Saleh et al., 2014).

BC emission factors are higher in some ICS than in traditional stoves (Grieshop et al., 2011). For example, in some rocket style stoves, the fuel consumption reduction cannot compensate the increase of BC emissions by fuel unit, resulting in higher total BC emissions (de la Sota, 2017).

GHG assessment

The climate change impact for each fuel is estimated through GHG emissions through the CO_2 equivalent (CO_2eq), with the Global Warming Potential over 100 years and the emission factors of each pollutant climate. When biomass is used, the emissions depend on its renewability, so it is necessary to incorporate the f_{NRB} as indicated in Equation 2:

$$GWP_{100} = EF_{CO2} \cdot f_{NRB} \cdot AFU + \sum_{i=1}^{n} EF_i \cdot AFU \cdot GWP_{100,i} \qquad (2)$$

where GWP_{100} is the Global Warming Potential over 100 years; EF is the emission factor; f_{NRB} = Fraction of Non-Renewable Biomass; AFU is annual fuel use; CO_2 is carbon dioxide; and i (from 1 to n) refers to each of the GHGs considered, other than C02.

Table 8 shows the GWP-100 reference values and emission factors for different fuel-stove combinations. In addition, (Smith et al., 2000) developed emission factors for different types of firewood, and (ESMAP, 2014) defined specific emission factors for Sub-Saharan Africa region.

Table 8. 100-Year Global Warming Potential (GWP100) values and emission factors for several fuel-stove combinations. Source: Grieshop et al., 2011.

	CO2 (g C kg1)	CO (g C kg1)	CH4 (g C kg1)	NMHC (g C kg1)	OC (g C kg1)	EC (g C kg1)	SO2 (g kg1)	PM2.5 (g kg1)
GWP-100	1	1.9	25	3.4	-35	455	-76	
W-Tr-U	418 (400–440)	35 (29–41)	4.8 (2.5–7.1)	3.2 (0.5–7)	4 (6–0.7)	1.5 (0.2–1.8)	0.01 (0–0.27)	8.5 (6–10)
W-Im-U	419 (398–440)	29 (14.5–43.5)	2.9 (1.3–4.8)	8.5 (1.7–15.3)	1 (5.1–0.6)	1.2 (0.3–1.9)	0.01 (0–0.27)	2.9 (2–9)

W-Im-V	415 (394–435)	29.1 (14.6–43.7)	2.9 (1.3–4.7)	5.6 (1.1–10)	1.5 (3.2–0.7)	2.1 (0.5–3.4)	0.01 (0–0.27)	4.1 (2.6–5.6)
W-Pat-V	441 (463–420)	8 (3–19)	0.9 (0.2–1.9)	0.3 (0–1.9)	1.1 (4.4–0.8)	0.8 (0.1–1.1)	0.01 (0–0.27)	2.1 (1.6–5.4)
W-Gas-U	394 (374–414)	2.2 (9.7–14.6)	1.2 (0.6–2.4)	4.1 (2–8.1)	0.4 (0.9–0.2)	0.3 (0.1–0.6)	0.01 (0–0.27)	1.1 (0.5–1.5)
W-Fan-U	462 (439–485)	2.6 (2.1–3.1)	0 (0–0.5)	1.6 (0.8–3.3)	0.1 (0.1–0)	0.1 (0.1–0.2)	0.01 (0–0.27)	0.5 (0.2–1)
Coal-U	685 (650–719)	30.3 (15.2–45.5)	7.7 (3.9–11.6)	2.4 (1.2–3.6)	3.1 (4.7–1.6)	4.4 (2.2–6.5)	0.15 (0.3–0.07)	8.7 (4.4–13.1)
Coal-V	736 (581–810)	40.9 (24.6–71.1)	2.6 (0.6–5.3)	1.3 (0.5–2.6)	1.5 (3–0.7)	2.1 (1–4.1)	0.88 (1.75–0.44)	4.1 (2.1–8.3)
Char-U	1113 (887–1338)	205.7 (173.1–238.3)	46.5 (33.4–59.6)	63.5 (47.5–79.4)	8 (11.2–4.9)	2.3 (1.4–3.4)	0.01 (0–0.27)	0.4 (0.2–0.9)
Ker-U	825 (802–850)	7.6 (4–26.6)	0.2 (0.1–0.8)	12.8 (6.4–19.2)	0.1 (0.2–0)	0.5 (0.3–1)	0.03 (0.07–0)	0.5 (0.3–1)
LPG-U	841 (799–883)	6.4 (5.1–7.7)	0 (0–0.1)	14.1 (7.1–21.2)	0.1 (0.1–0)	0.2 (0.1–0.4)	0 (0–0)	0.5 (0.3–1)

Another option for assessing the impact of short-lived pollutants is to monitor their effect after 20 years instead of 100 years, using GWP-20. Table 9 shows the reference data for calculations.

Table 9. Global Warming Potential to 20 years for short-lived pollutants. Source: IPCC, 2013.

Pollutant	GWP_20
BC	2421
OC	-244
CO	5.9
VOCs	14
SO_4	-141

For the calculation of emission reduction cooking projects, it is also possible to use the “Small-scale methodology: energy efficiency measures in thermal applications of non-renewable biomass” (UNFCCC, 2020). For SLCP, not covered by the methodologies used for Clean Development Mechanism (CDM) projects and other mechanisms established under the United Nations Framework Convention on Climate Change (UNFCCC), there can be used the methodology developed by the Gold Standard Foundation and a group of cookstove organizations (Gold Standard, 2016) so as to achieve a more precise assessment.

Electricity GHG emissions depend mainly on the mode of generation and as progress is made towards SDG target 7.2 to "substantially increase the share of renewable energy in the global energy mix", electricity emission factors are expected to improve. In addition to information published by each country, there are some useful electricity EF datasets (IEA, 2020b; IGES, 2020; UNFCCC, 2019).

2.3.5 Economy

Affordability is a significant barrier to accessing MECS, especially among low-income households and rural areas, even in countries with subsidised cooking fuels. The MTF considers that a cooking system is affordable if the fuel accounts for less than 5% of household expenditure. This 5% threshold is the same for electricity affordability and can be increased to 10% in temperate climates where electricity can be used for heating (IEA et al., 2019). Figure 18 shows that in some countries, cooking fuels are not affordable even for households with higher incomes, highlighting that income is a strong determinant of fuel election.

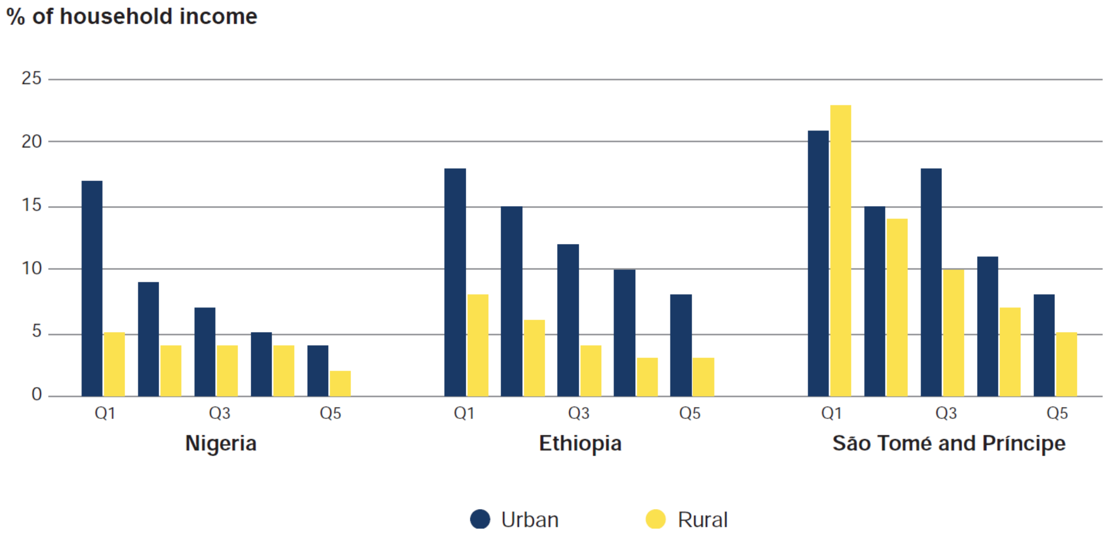

Figure 18. Fuel expenditure by income quintiles in Nigeria, Ethiopia, and Sao Tome and Principe. Source: ESMAP, 2020b.

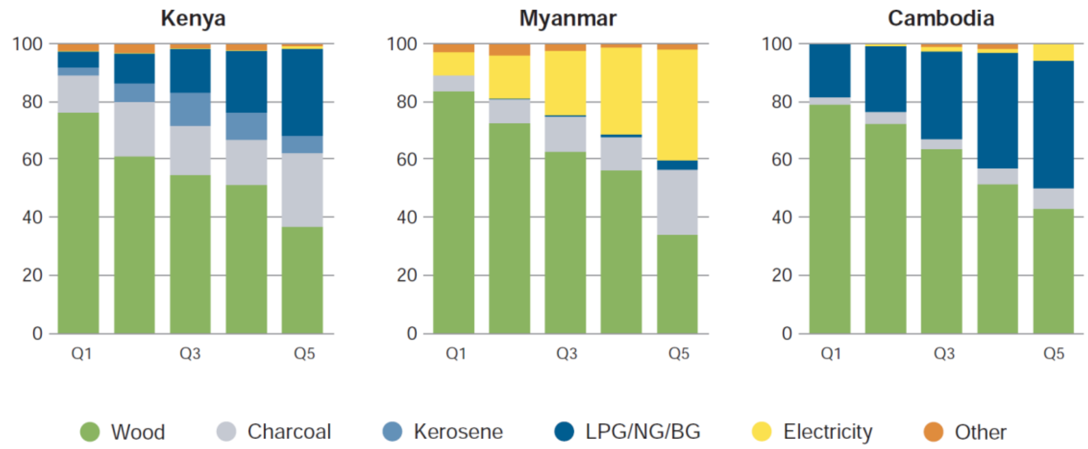

Figure 19. Primary fuel and electricity used for cooking by income quintile in Kenya, Myanmar and Cambodia. Source: ESMAP, 2020b.

Money spent by households on fuels passes in turn to other households and companies that work in the fuel value chain. The economic dimension of firewood and charcoal markets is important in many countries, and a shift to LPG and electricity can displace employment and income in rural areas from those employed in each sector. Moreover, the introduction of new types of stoves and electric appliances opens new employment opportunities in their manufacture and distribution.

At the national level, many countries spend substantial amounts subsidizing LPG and electricity, and the cost of transition to universal MECS by 2030 worldwide is estimated at USD1.5 trillion, which must be mobilized by the public and private sector (ESMAP, 2020b).

2.3.6 Cost-benefit analysis

To determine if the costs of a cooking program outweigh the benefits, a monetary valuation of them is made, and the net present value (NPV) is calculated considering a certain period of years and an annual discount rate.

Unit cost of energy and cooking stoves/appliances

Energy is a recurring cost in cooking. There is a great variation in the costs of different fuels depending on the country, as shown in Figure 20. In addition, there can be significant differences between different regions within a country, between urban and rural areas, between years, and between times of the year.

The price of charcoal depends on the regulation of its production established by each country, and on the degree and evolution of deforestation. The LPG price depends on the international market for importing countries, and the cost of electricity is heavily regulated in most countries and varies with the change in regulation or the generation costs.

The cost of cooking equipment can be an obstacle to its acquisition. There is a wide disparity in the prices of equipment as they depend on the type, model, quality, country, whether it is urban or rural, distribution network, etc.

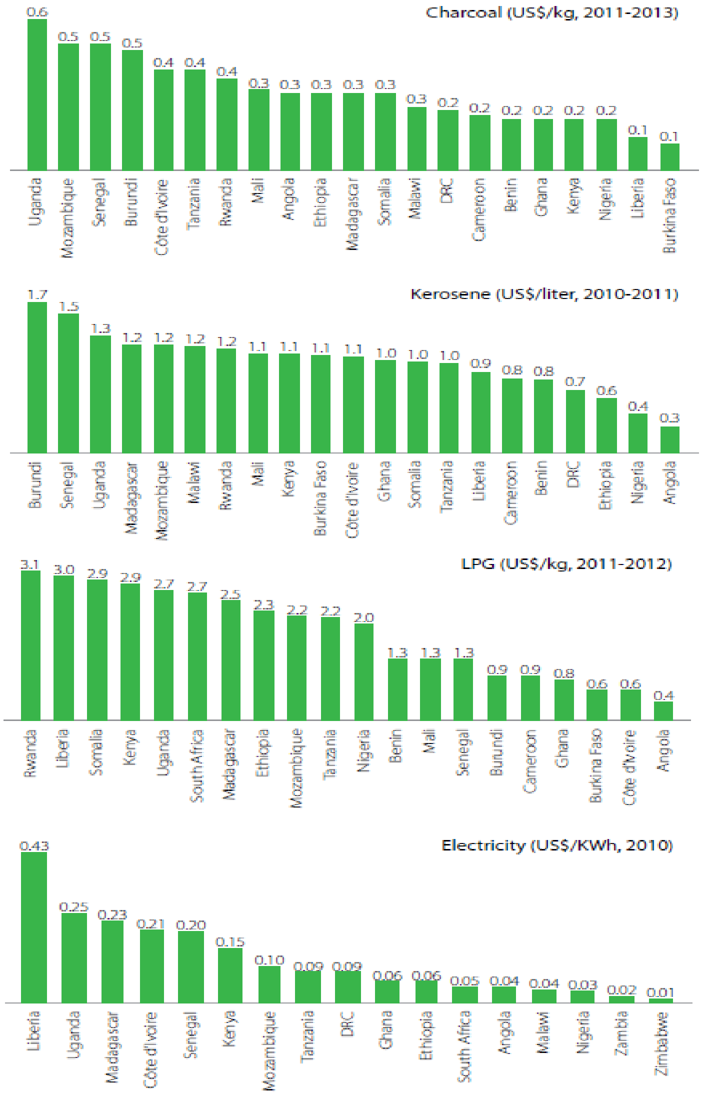

Figure 20. Cost of several cooking fuels and electricity in African countries. Source: ESMAP, 2014.

Monetary valuation

For time monetary valuation, the shadow salary can be used, according to the WHO recommendations (Mazorra et al., 2020). It can be considered that all time saved has an economic value, or that only a percentage is applied to productive values that represent an economic value (e.g., 50%). (ESMAP, 2020b) makes a conservative estimation at US$0.54 per hour in LMICs.

For DALYs monetary valuation, the shadow salary can again be used, considering the time an adult stops working or has to spend caring for a child. The costs of the health system for the treatment of these diseases can also be considered. (ESMAP, 2020b) estimates one DALY at 5 times GDP per capita, and a death at 70 times GDP per capita.

Carbon emissions can be valued at the price of CO_2eq tonne in the international market or considering the social cost of carbon, it means the present value of future damage to global society, US$45.92/t in 2019 (ESMAP, 2020b).

WHO has developed a tool called Benefits of Action to Reduce Household Air Pollution (WHO, 2020) for medium-term planning (15 years), which uses monetary valuation differentiating between private and public costs, and including the public costs, the subsidies and the organisational costs of developing programmes. (Das et al., 2021) presents two cases using this tool in Nepal.

2.4 Cooking practice

2.4.1 Cooking transition process

The transition from traditional to modern fuels and devices has been explained by the ''energy ladder'' model, which suggests that with increasing affluence, a progression is expected from traditional biomass fuels to more advanced and less polluting fuels. (O. R. Masera et al., 2000) observed that this model did not reflect the pattern of household accumulation of energy options observed in Mexico, and proposed the "multiple fuel" model, where the new fuels did not fully displace the old ones, leading to a fuel stacking process (Figure 21). Today, fuel stacking is considered the normal way of cooking transition into MECS, especially among households that have access to clean fuels and electricity, and in urban and peri-urban areas. Households usually stack with the next-cleaner fuel; for example, if they use firewood as primary fuel, then they use charcoal for stacking.

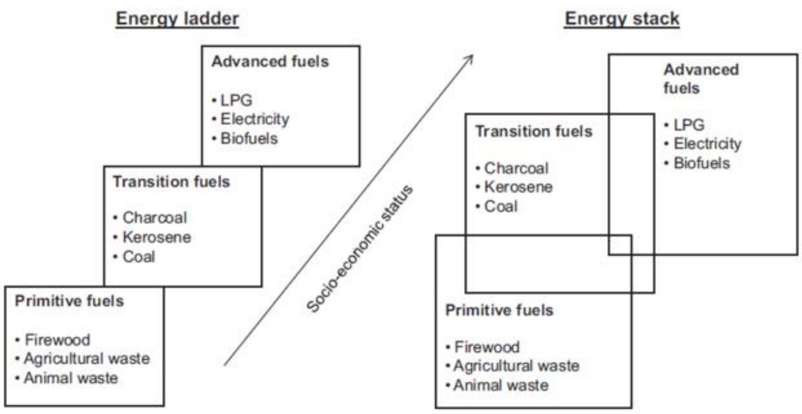

Figure 21. The processes of energy transition. Source: Adapted from Kroon et al., 2013.

It is also common to observe the use of multiple technologies with the same fuel; for example, the introduction of firewood ICS does not fully displace the three-stone fires, leading to a technology stacking process. Currently, the term "stacking" is used to refer to the use of multiple cooking solutions in the same household, multiple fuels and/or multiple technologies (ESMAP, 2020b).

Stacking is a highly persistent/prevalent process, even when clean fuels and electricity are heavily subsidized. For example, in Ecuador, 44% of households that use LPG as primary fuel continue using wood at least once a day (Gould et al., 2020). In a program in India for the introduction of induction stoves, the new equipment replaced LPG as the secondary fuel but not firewood as the primary one (Banerjee et al., 2016).

There are several reasons to stack (Bilich et al., 2021; ESMAP, 2020b; Ochieng et al., 2020; Ruiz-Mercado & Masera, 2015):

- New technologies do not meet non-cooking needs.
- The inability of any single cooking device (traditional or improved) to fulfil all stove applications.
- Time savings from being able to prepare multiple meals simultaneously with several stoves.
- Preference for preparing some meals on specific cookstoves.
- Providing a back-up system when the cooker or primary fuel is not available.
- The impossibility of accommodating large pots to cook large quantities of food.
- In the case of induction stoves, the need for ferromagnetic pots, and in the case that these are too thin (without a diffuser base), the risk of burning food if not cooking carefully.

Stacking has concerned promoters of clean cooking programmes because often the introduction of a clean technology has not displaced the polluting one, hindering health improvements. In this sense, it is possible to distinguish two types of stacking behaviour:

- Dirty stacking: using secondary non-clean fuels with primary clean fuels
- Clean stacking: the use of clean fuels for stacking by households that primarily use non-clean.

Clean stacking behaviour is a spontaneous process in settings with electricity supply that is reliable and affordable, as in some parts of India, where electric cooking appliances already carry out cooking tasks everywhere (Smith et al., 2014). This stacking process can yield positive near- and longer-term results if traditional stove users try modern fuels for small cooking tasks, such as boiling water or reheating food. Experimentation with lower emission solutions may facilitate learning and increase the likelihood of adoption over the longer term (ESMAP, 2020b). An example of this new approach is occurring in Mexico, where the joint dissemination of iron-plated ICS and LPG enables a decrease in the use of traditional cuisines in regions.

2.4.2 Cooking system allocation

<u>Dishes and cooking tasks</u>

Understanding what is cooked and how often allows for a better adjustment of cooking technology to the needs of a home. For example, a typical menu in East and South Africa consists of (Leary, 2019):

- Heavy foods: boiling for more than one hour, sometimes with previous or final frying (e.g., beans).

- Staples: boiling around half an hour, sometimes with stirring (e.g., rice and porridge).
- Quick fryers: frying for 5–15 minutes, sometimes with stirring to prevent burning.
- Deep fryers: food submerged in oil at high temperature.
- Flat breads: at medium heat and access to turn the bread.

The most frequent cooking tasks are:

- Boiling (the temperature of water changes the state over 100^{o}C, large evaporation, big bubbling)
- Simmering (the temperature between boiling and 90^{o}C, less evaporation, small bubbling)
- Frying
- Grilling
- Baking
- Re-heating

Efficient cooking system allocation

In addition to using energy efficient equipment, another strategy to reduce energy consumption is to allocate the equipment to tasks that best fit for energy efficiency, cooking style, or cultural preferences. In general, households have to use modern fuels and electricity for quick tasks, and biomass for heavy foods (Scott & Coley, 2021). In Mexico, when there is stacking with LPG, this fuel is used to reheat dishes and make fast meals, such as heat water or milk for breakfast (Medina et al., 2019). In Tanzania, LPG is preferred for frying (Leary, Scott, et al., 2019). In rural India, induction stoves are majorly used for cooking rice and vegetables/curries, re-heating food and preparing tea, but they are hardly ever used to prepare chapatis, a staple food in this country (Banerjee et al., 2016).

(Ruiz-Mercado & Masera, 2015) have made a proposal to allocate different tasks to ICS, LPG, and open fire stoves in Central Mexico (Figure 22).

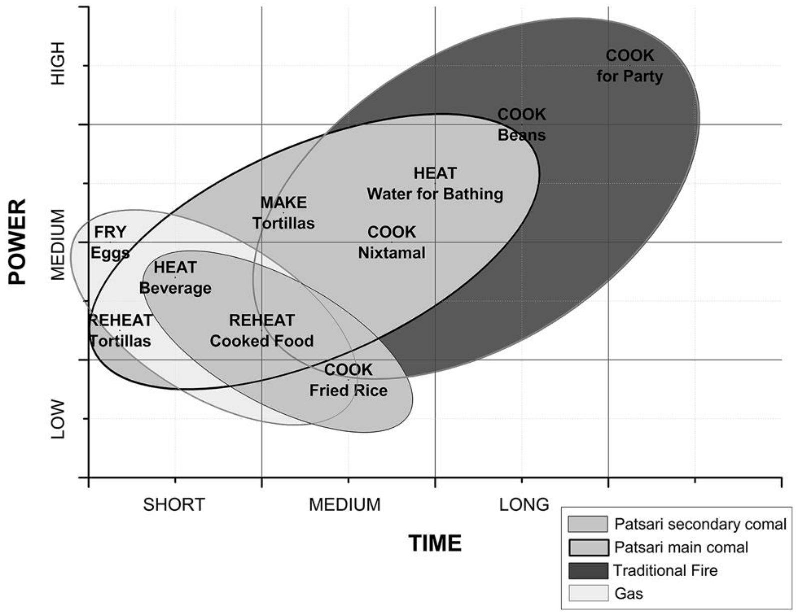

Figure 22. Definition of niches in the context of stove stacking for the case of the Patsari chimney stove, traditional open fires, and gas stoves in Central Mexico. Source: Ruiz-Mercado, 2015.

With an initial electric set consisting of a versatile hob (hotplate/induction stove/infra-red stove) and an efficient EPS, a balance can be found between energy efficiency and convenience for the next task location:

- Re-heating: hob.
- Heating liquids for beverages: hob for small quantities and EPC for large quantities.
- Flat breads: hob.
- Quick fries (e.g., grilled food or eggs): hob.
- Quick fries (e.g., sauté or sauces): hob, but an EPC can be used if cooking later.
- Deep fries: EPC.
- Boiling/simmering for staples (e.g., rice): EPC.
- Boiling for heavy foods: EPC.

For specific tasks, this initial set can be complemented with other efficient equipment, such as a rice cooker, kettle or microwave oven.

Energy saving techniques

Regardless of the cooking technology chosen, there are numerous techniques that can be used to save energy (Table 10).

Table 10. Potential energy savings with various cooking techniques. Source: Hager & Morawicki, 2013.

	Techniques	Reduction in energy (%)
Cooking method	Simmering (90ºC) rather than boiling (100ºC)	69–95
	Steaming rather than boiling	9–56
	Passive cooking	17–23
	Simmering with a pot lid	50–85
	Baking at lower temperatures	4–13
Cookware	Using a pan with a diameter larger than the heat source	31–40
	Using non-distorted flat pans	42–68
	Using insulated materials to retain heat	42–63
Food volume	Filling pot to capacity	20–49
	Cooking larger quantities	78–83
	Baking more than one portion at a time	43–75
Monitoring product	Monitoring internal temperature	19–50
	Stirring	3–14
Soaking	Soaking prior to cooking (for certain foods)	3–19

2.5 Conclusions

The measurement of target 7.1.2. on access to affordable, reliable and modern energy cooking services has evolved from a measure of emissions and efficiency of cookstoves (clean cooking) to the Multi-Tier Framework with six attributes (MECS), increasing the number of people without access from 2.4 billion to 4 billion in 2019.

Most ICS do not meet the WHO AQG, so they are generally not an enabling technology to achieve target 7.1.2. indoors. The policies of promoting ICS that have been implemented in recent years should be reconsidered so that they can only be used outdoors with ventilation systems that guarantee WHO AGQG.

Personal exposure to high concentrations of cooking pollutants is the main reason for the health impacts of cookstoves, and their reduction should be an objective of all cooking transition programmes. Exposure depends not only on the fuel-stove combination but also on space, ventilation, and personal practices, so these variables must also be considered.

eCooking allows the use of a wide variety of equipment. There are important differences between the energy efficiency and versatility of different equipment, and the use of a combination of equipment should be promoted to optimise these two variables together.

There is great variability in the energy demand for cooking, depending on the combination of fuel-stove and electric cooking appliance used, but also on the type of food being cooked, the number of members in the household, or the method of cooking. With a mixture of conventional and energy-efficient appliances, the average daily consumption for a typical household is 0.88-2.06 kWh/day, which requires a Tier 4-5 level of access to electricity.

There are various methodologies for measuring the impacts of cooking on health, gender equality, the environment, climate change and the economy. There is no tool that integrates all impacts.

Cooking impacts are highly contextual and depend on many boundary variables, so extrapolating data from one context to another, risks incorporating very high margins of error. In many cases, fieldwork is required to obtain reliable data, which makes measuring impacts difficult and expensive.

The normal process of cooking transition is stacking, which makes it difficult to reduce exposure to pollutants but allows for the progressive introduction of new technologies. An efficient cooking system allocation would optimise convenience of use and energy efficiency.

3. ELECTRIC COOKING AND ELECTRIFICATION INTEGRATED PLANNING. NYAGATARE CASE STUDY

Research question: **How should the eCooking demand for electrification planning be modelled and what would be the impacts of incorporating eCooking in the electrification of areas not yet electrified?**

This chapter is based on the article first authored by the author of this thesis and published in the journal Energies: "Joint Optimal Planning of Electricity and Modern Energy Cooking Services Access in Nyagatare" (Sánchez-Jacob et al., 2021), and takes some ideas from previous work carried out for the World Energy Outlook 2019 (IEA, 2019), documented in the MIT Center for Energy and Environmental Policy Research working paper “Investigating the Necessity of Demand Characterization and Stimulation for Geospatial Electrification Planning in Developing Countries” (Lee et al., 2019).

3.1 Introduction

The dissemination, adoption and prolonged use of electric cooking will depend on multiple factors, but technical and economic feasibility must be a precondition. There are many studies about eCooking, as are mentioned in other chapter; however, to date, no published methodology exists for the integration of the provision of access to modern energy cooking services into electricity planning at large-scale geographical-scale using geospatial techniques, and this study seeks to contribute to filling this gap.

This chapter describes a preliminary study to lay the foundations for the integration of electrical cooking and MECS in the electrical planning of unserved areas from the electricity supply side. The three main objectives are: 1) to develop a methodology; 2) to discuss reference values for the main variables used; and 3) to test the methodology and values in a real scenario in order to validate it, drawing some initial conclusions and identifying new areas of research for more detailed analysis.

The Reference Electrification Model (REM) is used to run the cases presented. REM is a mature large-scale planning tool that finds the least-cost electrification solution, usually a combination of standalone systems (SAs), microgrids (MGs), and grid extensions (GEs), for an underserved region using heuristic optimization (Ciller et al., 2019). To date, REM has been used in planning projects at the country level in Sub-Saharan Africa, South Asia, and South America (MIT & IIT-Comillas, 2021; Waya, 2021).

Three scenarios of the same region are studied with REM. The first, denominated the Basic Scenario, supplies the electricity to meet just the basic services in a household. In the second, the Complete Scenario supplies the basic services and electricity for cooking the entire daily cooking load. The third scenario, the Stacking Scenario, covers basic services with half the daily cooking load carried out with energy-efficient electric appliances and the other half with another cookstove. A stacking scenario, comprising the use of multiple stoves and fuels in the same household, was analysed because it is the usual process of transition from traditional to clean cooking solutions. Clean-stacking behaviour, in which cleaner cooking solutions are adopted by users of traditional cookers, even for such small cooking tasks as boiling water or refrying, results in reduced use of a lower-tier alternative, facilitates learning, and increases the likelihood of its adoption over the longer term.

The country chosen to test the methodology is Rwanda. It is a landlocked country of East Africa, with a surface area of 26,338 square kilometres and a population of 12.3 million people in 2018, of which more than 80% live in rural areas. Having a Gross National Income (GNI) per capita of USD 780, it is considered a low-income country by the World Bank (World Bank, 2021b).

The results of the analysis show that electric cooking substantially changes the least-cost distribution of the electrification modes and the kWh cost, and demonstrate that electric cooking can be cost-competitive compared to LPG and charcoal in grid-connected households. In addition, clean stacking with electricity can be a transitional means of meeting MECS. Cooking with energy-efficient electric appliances and renewable energy in grid and off-grid settings is the most effective way to meet the three targets of SDG 7—universal access, efficiency, and renewable energy—and to contribute towards complying with the Paris Agreement.

3.2 Rwanda and Nyagatare District

Nyagatare District is in the Eastern Province, occupying the north-eastern extremity of Rwanda (Figure 23). It has a surface area of 1741 km^2, with an estimated population of 550,000 people in 2018 (NISR, 2015a), resulting in a population density of 316 inhabitants per km^2. Here it will be assumed that four people inhabit each household, the same as the national average in the rural areas (NISR, 2015b).

Figure 23. Nyagatare District. © Google Map. © d-maps.com.

According to the Rwanda Energy Access Diagnostic Report Based on the Multi-Tier Framework, less than 0.1% of the population has access to MECS. A share of 99.6% of households cook with biomass fuels, only a quarter of households cook outdoors, and only 15.2% of households that cook indoors use an extraction system. A share of 76.5% of households spend over 7 h per week acquiring and preparing cooking fuel. Household air pollution, mainly attributable to biomass cookstoves, produces 7425 deaths and 340,000 Disability-Adjusted Life Years (DALYs) annually (IHME, 2021). To address this situation, the Rwandan Government has planned to reduce the reliance on firewood from 83% to 42%, and to increase the LPG penetration to 40% in urban areas by 2024 (Development Bank of Rwanda et al., 2021).

Taking into account the attributes of MTF for electricity (Bhatia & Angelou, 2015), but excluding affordability, 73.2% of the nation is considered without access, 2.8% with Tier 1 access, 2.1% with Tier 2, 10.3% with Tier 3, 7.8% with Tier 4, and 3.7% with Tier 5, with lower levels in rural areas. The Government has set a target to achieve 100% electrification, of at least Tier 1, by 2024, and a National Electrification Plan (NEP) has been developed with REM (REG, 2019).

3.3 Methodology

3.3.1 Scenarios

To compare the different alternatives for achieving electricity and MECS access, three future scenarios were studied:

- Basic Scenario—electricity supplies basic services in every household in Nyagatare District.
- Complete Scenario—in addition to covering basic services, the entire daily cooking load is carried out with electricity in every household in Nyagatare District.
- Stacking Scenario—in addition to covering basic services, half the daily cooking load is carried out using energy efficient electric appliances and the other half with other cookstoves in every household in Nyagatare District.

In all three scenarios, all households are assumed to have the same electricity demand. For the design of the scenarios, the starting point is the situation in 2018, and the target date is the date established to meet SDG 7, 2030.

3.3.2 Reference Electrification Model

REM approaches electrification planning with a very high modelling complexity (Ciller & Lumbreras, 2020). The model operates with a high spatial resolution, calculating detailed network designs for microgrids and grid extensions whose layouts go down to the end-buildings. These network designs are obtained considering frequent electric constraints and topographical features, such as terrain slopes and forbidden areas (Drouin, 2018).

REM also works with a high temporal resolution, representing the demand of each consumer and the renewable potential (solar irradiance) with an hourly profile. The model optimizes the generation designs of microgrids and standalone systems using a heuristic method that simulates the hourly dispatch of potential generation designs (Ciller, de Cuadra, et al., 2019).

This model is being continuously improved by the integration of new functionalities or enhancement of the optimality of its algorithm, but this study focuses on applying the tool to several cases and analysing the corresponding results. Therefore, this study presents an application of previously developed methods.

REM Inputs and Outputs

REM requires substantial information concerning the analysis region to operate. The inputs of the model include the following data (Ciller, Ellman, et al., 2019):

- The location and demand of each consumer.
- The location, reliability, and energy cost of the distribution network.

- The catalogue of generation components, which includes techno-economic data of solar panels, batteries, diesel generators, inverters, and charge controllers.
- The catalogue of network components, which includes techno-economic information about transformers and lines.
- The topographical features of the terrain, such as altitudes and protected areas.
- The hourly solar irradiance for a year, which is used to calculate the generation of solar panels.
- Techno-economic and configuration parameters, such as discount rates, cost of diesel, and labour cost.

REM provides the following outputs when it calculates the least-cost solution for a region:

- The grouping of consumers into clusters and the best electrification mode for each cluster to achieve a least cost overall electrification plan with a combination of individual standalone systems, microgrids and grid extensions.
- The generation design of each microgrid and standalone system. REM provides detailed information regarding the generation components included in each design and the corresponding costs.
- The distribution network of each microgrid and grid extension. The electrification solution includes a bill of materials and the location of the lines and transformers needed for each design.
- Relevant information concerning the electrification solution, such as the amount of demand served and the reliability of the systems, overnight costs, and costs per kWh of demand served.

REM Workflow

REM operates following a process comprised of five sequential steps, which are briefly described in this section:

- Data preparation. This step aims to collect the input information that REM needs and convert it to the specific formats that the model requires. Satellite imagery and machine learning methods based on convolutional neural networks can estimate the location of the consumers, although there are publicly available datasets such as the High Resolution Settlement Layer (HRSL) which approximates population density in cells of $30 \times 30\ m^2$ (Facebook Connectivity Lab and Center for International Earth Science Information Network - CIESIN - Columbia University, n.d.).
- Microgrid generation. REM optimizes the generation designs of several microgrid representatives of the analysis region and stores the corresponding information in a look-up table. If REM needs information concerning generation costs of the remaining microgrids, the model quickly obtains it by interpolating amongst the designs stored in the look-up table.
- Clustering. The model groups the consumers into potential microgrids and grid extensions, analysing the trade-offs between costs. For example, large microgrids have substantial network costs, but they benefit from economies of scale in generation.

- Final designs. REM optimizes the network designs of the potential microgrids and grid extensions, determining the final electrification solution for the analysis region and the corresponding costs.
- Process results. The model generates graphical and statistical outputs that contain critical information about the case study. For example, REM generates files with the distribution networks of microgrids and grid extensions, which can be projected onto Google Earth.

3.3.3 Electrification Planning

To simulate scenarios with REM, it is necessary to identify the position of every consumer and to define user profiles.

The buildings across Nyagatare District were identified using satellite imagery from the Google Maps API and a convolutional neural network for semantic segmentation with human-based manual corrections (Lee, 2018). A total of 74,315 buildings were identified and georeferenced: 74,248 households, 22 cell offices, four markets, four primary schools, 29 pre-primary schools, five secondary schools, and three telecom towers. In Nyagatare District, approximately 99% of buildings to be supplied with electricity are household dwellings.

The parameters used for the scenarios are similar to those used in the 2018 NEP design (REG, 2019):

- Cost of energy from the central grid: 0.9 $/kWh
- Reliability of the central grid: 100%
- Catalogue of components and network standards that apply at national level: equal for grid extension and grid-compatible microgrids
- Catalogue of components for off-grid generation available internationally
- Discount rate: 8%
- Smallest microgrid must have at least 10 customers or 5 kW
- Administrative charges per grid-connected customer: 9 USD/year
- Administrative charges per microgrid customers: Medium size microgrid (100 customers): 16 USD/year. Large size microgrid: Asymptote at 9 USD/year
- Administrative charges per isolated customers: 60 USD/year
- Average cost of diesel: 1.2 USD/L
- Average cost of labour: 1.6 USD/hour

The administrative charge per isolated system is based on a “service provision” business model in remote areas where the provider guarantees a high quality of service at all times—365 days a year, 24 hours a day. In other business models, such as the sale of photovoltaic kits on the open market, the charge may be lower, but this is at the expense of quality of service. Capital cost over the economic lifetime of the asset and operational cost are calculated for each technology assuming full recovery of the investment. The expenses incurred on a non-annual basis are converted to an annuity with a discount rate.

The electricity demand of each consumer depends on several factors such as socioeconomic data and climate information, among many others. REM assigns a one-hour-resolution yearly demand profile to each consumer and distinguishes between two types of demand: critical demand, which accounts for essential consumption, and non-critical demand, which accounts for non-essential consumption. REM usually assigns substantial penalties for the critical demand left unsupplied, while non-critical demand is penalized to a lesser extent if it is not met.

3.3.4 Household Electricity Demand

In this study, 1 kWh/day per household is used as “the basic consumption package” in all scenarios. This amount coincides with Tier 3 of the MTF scale and meets the current demand of a large part of recently electrified rural households in Kenya (Fobi et al., 2018), where the rural area could be compared to the one in Nyagatare District.

The hourly profile of consumption expected from the average customer, household, and non-household users, is taken from NEP and was determined from average feeder data provided by the Energy Development Corporation Limited (EDCL) and the field study for the village of Karambi (Figure 24). It is assumed that the demands of all users are a multiple of the average customer. Therefore, the electrical profile for basic services in households is eleven times the basic profile and is the same for every household.

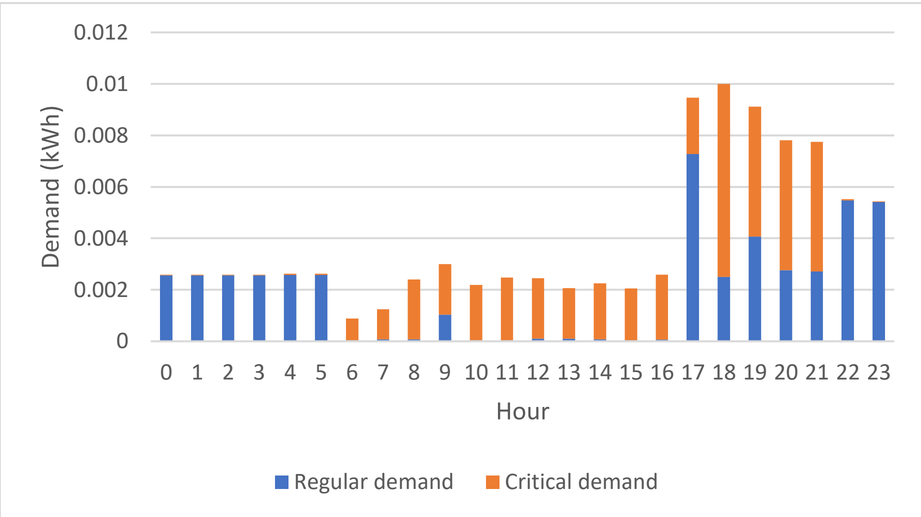

Figure 24. Basic profile in the design of the National Electrification Plan (NEP) in Rwanda. Source: REG, 2019.

There are no data available for Rwanda regarding the median daily per capita consumption of electricity for cooking, when using only electricity for cooking with a mix of efficient and inefficient appliances. For this reason, the data for Kenya (0.49 kWh) and Tanzania (0.49 kWh) were taken as the best available approximation due to their geographical and cultural proximity. Considering four people per household (HH) and rounding up to have a worst-case margin, 2 kWh/day/HH is assumed as the demand for cooking all the meals with electricity in the Complete Scenario.

In accordance with (ESMAP, 2020a), in a fuel stacking scenario in which half the daily cooking load is carried out using a mix of electric energy-efficient appliances, daily electricity consumption is projected to be just 0.30 to 0.67 kWh per household, and rounding up to have a worst-case margin, 0.7 kWh/day/HH, is assumed for the Stacking Scenario.

As there are no demand profiles for electric cooking available for Rwanda, a combination of the normalized 24 h load profile from households in Kenya and Tanzania adapted to an hourly distribution was used. To consider the worst scenarios, when the load is only for one household, the entire demand is concentrated in 1 h (at 19), for five households it is distributed over 3 h (at 7, 13 and 19), for 10 households over 6 h (at 7–8, 12–13 and 18–19), and finally for 50 customers over 15 h (from 6 to 9 and from 11 to 21). This makes the profile as close as possible to the combination of the Kenya and Tanzania profiles adapted to the hourly format (Figure 25). This provision was made to consider the most disadvantageous situations for batteries and inverters in off-grid systems when a large part of the daily demand must be supplied in a short period of time.

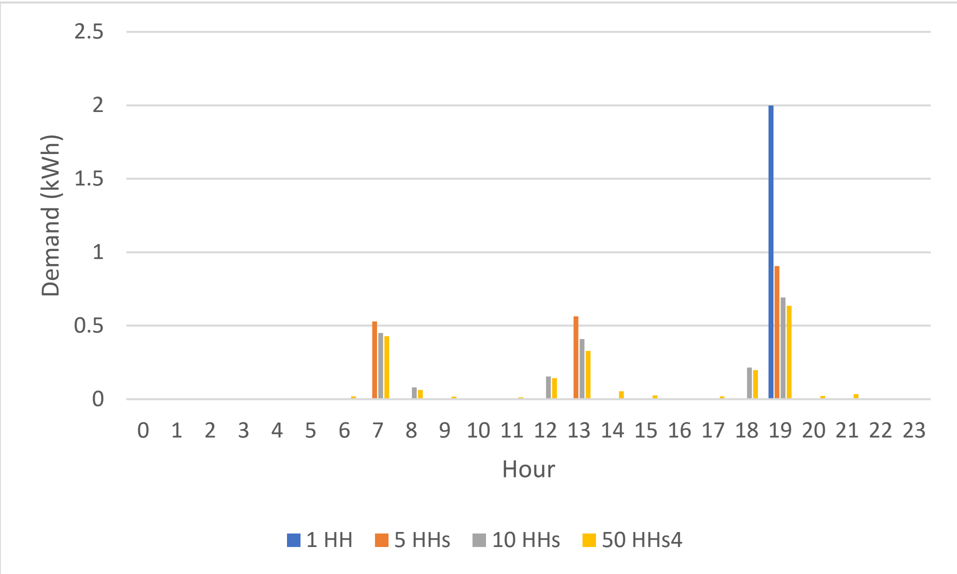

Figure 25. Electric cooking demand for the Complete Scenario for 1, 5, 10, and 50 households. Source: own elaboration.

3.3.5 Cooking Alternatives

Cooking with electricity is compared to the three most common alternatives, namely cooking with firewood, charcoal, and LPG. The price of an intermediate improved cookstove ranges from USD15 to USD30, whereas an energy-efficient electric appliance is normally more expensive, with basic EPCs typically retailing between USD50 and USD100 (ESMAP, 2020a). One robust LPG stove costs USD30 to USD60 (Puzzolo et al., 2020). Two stoves or electric appliances per household are considered because it is common for more than one cooking task to be undertaken at a time. In the stacking scenarios, one stove or electric appliance is considered for each technology.

The consumption for each cooking mode is based on Kenyan and Tanzanian diaries. In the Stacking Scenario, consumption is half for LPG, charcoal, and firewood, but less than half in terms of electricity because the use of a mix of energy-efficient appliances is assumed. LPG and electric appliances are estimated to have a lifetime of 5 years, compared to 2 years for charcoal and firewood stoves given the rapid deterioration of materials due to prolonged exposure to very high temperatures. Maintenance costs are included in the initial capital cost. Table 14 summarizes the main values.

Table 11. Average cost and consumption of cooking appliances and stoves. Source: own elaboration.

	LPG Single Burner	Charcoal Stove	Wood stove	Energy-Efficient Electric Appliance
Cost (USD)	45	22.5	22.5	75
Lifetime (years)	5	2	2	5
Annual cost (USD)	9.0	11.3	11.3	15
Consumption as sole source (kWh/day or Kg/day)	0.28	1.75	3.5	2
Consumption in Stacking Sc. (kWh/day or Kg/day)	0.14	0.875	1.75	0.7

Firewood and charcoal prices depend on their availability and legal regulation. When LPG and cylinders are imported, commodity pricing fluctuations, local currency inflation, and shortages in foreign currency exchange can influence fuel supply (Puzzolo et al., 2019). To avoid price uncertainty in the 2030 horizon, instead of calculating the cost of cooking for each fuel in each scenario, cooking cost with electricity is calculated and then the "breakeven price" of each fuel that matches this cost is also computed. For example, if the breakeven price of LPG is USD1.00, it means that when the cost of LPG is lower than USD1.00, it is more economical to cook with this fuel, but when it is greater than USD1.00, it is economically more advantageous to cook with electricity.

The price of LPG, charcoal and firewood varies from location to location depending on the distance to supply centres, availability and demand. When the price is known, the most economical cooking option can be determined.

3.3.6 Greenhouse Gases Emissions

The climate change impact for each fuel is estimated through GHG emissions, using the Global Warming Potential over 100 years (GWP-100) to estimate the CO_2 equivalent (CO_2eq). The Fraction of Non-Renewable Biomass factor (fNRB) is used in accordance with Equation 3 and data used are shown in Table 12.

$$CO_2eq = FC * [(EFCO_2 * fNRB) + (EFCO * GWPCO) + (EFCH4 * GWPCH4) + (EFBC * GWPBC)] \quad (3)$$

where CO2 = carbon dioxide; CO = carbon monoxide; CH4 = methane; BC = black carbon; FC = fuel consumption; EF = emission factor; fNRB = Fraction of Non-Renewable Biomass; GWP = Global Warming Potential over 100 years.

Table 12. GWP-100 (IPCC), fraction of Non-Renewable Biomass (fNRB) (Drigo et al., 2014), emission factors for LPG (Smith et al., 2000), and common SSA charcoal stoves, firewood stoves, and kiln process (ESMAP, 2014), in grams of emissions per kg of fuel burned.

	GWP100	LPG	Charcoal	Firewood	Charcoal Kiln
CO_2		3085	2335	1519	1800
fNRB[1]		100.00%	58.45%	58.45%	58.45%
CO_2 non-renewable	1	3085	1364.8	887.9	1052.1
CO	1.9	15.00	192.5	70.00	225.00
CH_4	28	0.05	10.2	3.90	44.60
BC	460	0.01	0.07	1.90	5.47
CO_2eq		3120	2048	2004	5245

1. Rwanda average for low and high productivity variant, considering biomass from deforestation and afforestation.

The emissions are only calculated in the cooking process. For charcoal production, the impact on GHG emissions and biomass consumption is calculated due to concerns about its high impact (MARGE, 2009). It is assumed for 1 kg of charcoal produced, 5 kg of wood is consumed (GIZ, 2014).

Due to the commissioning of new peat and methane plants in Rwanda, the share of renewables will fall from 62% in 2016 to 38% in 2021. With the phasing in of new hydropower plants, the share is expected to reach 44% in 2025. New plants will not only meet the demand but there will also be significant over-capacity. The share of renewable energy by 2030 is estimated to be between 44% and 60% (Ministry of Infrastructure, 2016). In this study, 410 CO_2eq grams per kWh emission factor is assumed by 2030 (Gouldson et al., 2018). Microgrids and isolated systems are considered emission-free because they are supplied with PV systems.

3.3.7 Sensitivity Analysis

Several uncertainties affect the results. The cost of electricity supplied from the grid and the cost of the equipment for PV systems influence the fraction of customers with each electrification mode, the kWh cost in each mode, and the total cost of electrification. In the 2018 NEP design, 0.12 USD/kWh was used for electricity supplied to the grid, but it is expected that the new projected generating capacity will reduce the cost by 2030. In sensitivity analysis 1, 0.09 $/kWh is used as the central hypothesis, and then the impacts of a higher—0.12 USD/kWh—and lower—0.06 USD/kWh—cost are analysed. In sensitivity analysis 2, the PV equipment cost taken from an international catalogue is used (Moretti et al., 2019; REG, 2019) and then the impacts of reductions of 10% and 20% are analysed.

In the 2018 National Electrification Plan of Rwanda, the projected demand for basic services was lower than 1 kWh/day. Two types of residential customers were identified: 50,777 customers with a very low demand of 50 Wh/day, Tier 1 of the MTF scale, and 23,471 customers with a low demand of 450 Wh/day, Tier 2. Regardless of whether the demand was 50 Wh/day or 450 Wh/day, all households that, according to REM were to be electrified with isolated systems, would be supplied with the same small USD35 DC

Solar Kit, which would be upgraded as needed in the future (REG, 2019). In sensitivity analysis 3, the changes involved in using the National Electrification Plan basic consumption instead of 1 kWh/day demand is analysed.

3.4 Results and Discussion

3.4.1 Fraction of Households by Electrification Mode and Total Cost Per kWh

Each scenario has a different distribution of the three electrification modes and a different unit cost for the electricity supplied.

The most frequent electrification mode in all three scenarios is grid extension, with 92% of consumers electrified in the Basic Scenario. In the Complete Scenario and the Stacking Scenario, the fraction of connected households increases to more than 96%. In the Basic Scenario, the second most frequent option is isolated systems, whereas in the Stacking Scenario and the Complete Scenario, it is microgrids (Figure 26 and Table 13).

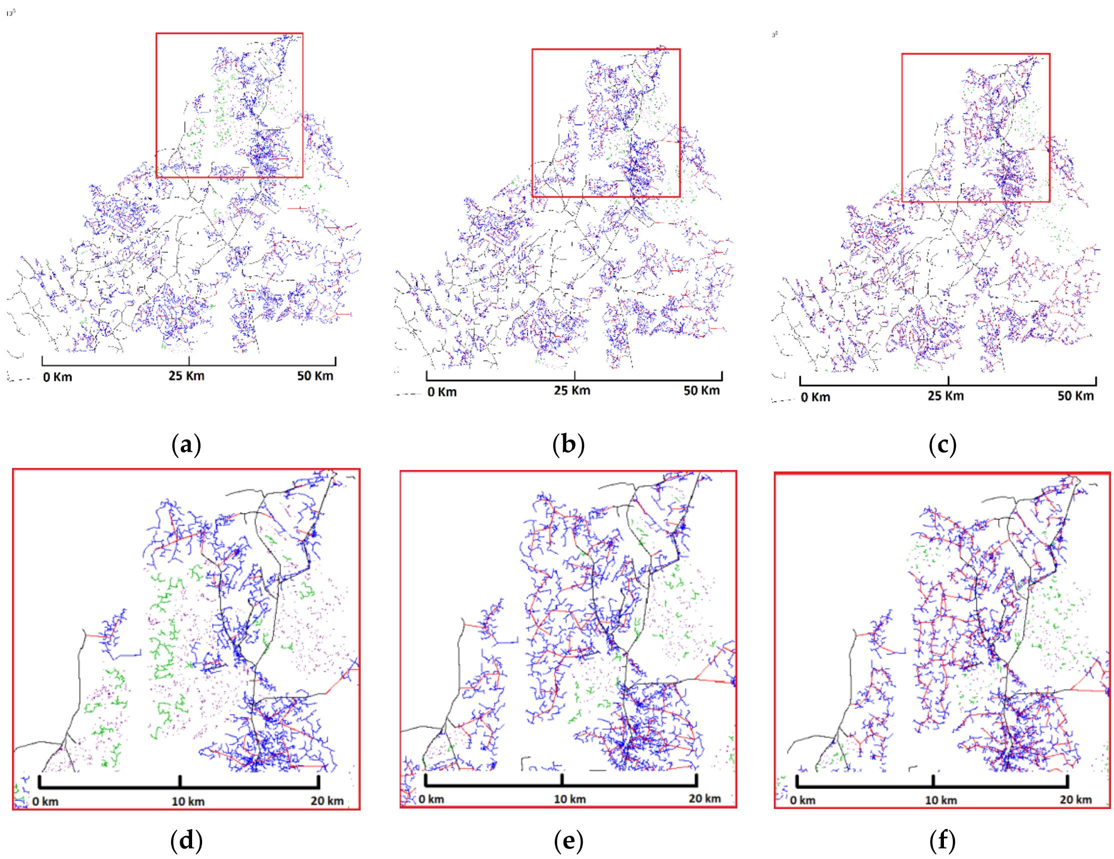

Figure 26. Distribution of grid extensions (blue), microgrids (green), and isolated systems (red dots) in Nyagatare and a framed area for the Basic Scenario (**a**) and (**d**), Stacking Scenario (**b**) and (**e**), and Complete Scenario (**c**) and (**f**). Source: own elaboration.

The average cost in the Basic Scenario is 0.31 USD/kWh, with an important reduction per unit cost in the Stacking Scenario and Complete Scenario when electricity is used for cooking (Table 13). The higher the consumption, the lower the per unit cost. In the Complete Scenario, there is a 29.24% average cost reduction—31.50% for microgrids, 30.31% for isolated systems, and 26.34% for grid extension—and in the Stacking Scenario, a 17.82% average cost reduction—17.68% for microgrids, 16.98% for isolated systems, and 14.88% for grid extension. The average cost reduction in the Stacking Scenario is higher than the reduction in the three electrification modes because the fraction of households changes between the Stacking Scenario and the Basic Scenario (Figure 27).

Table 13. Fraction of households and cost per kWh by electrification mode in the Basic Scenario, Stacking Scenario and Complete Scenario. Source: own elaboration.

Scenarios	Fraction of Households			HH's Total Cost Per kWh (USD/kWh)			
	Microgrids	Isolated Systems	Grid Extensions	Microgrids	Isolated Systems	Grid Extensions	Average
Basic Sc.	3.66%	4.01%	92.33%	0.478	0.593	0.291	0.310
Stack. Sc.	2.21%	1.54%	96.25%	0.393	0.492	0.248	0.255
Comp. Sc.	2.74%	0.94%	96.32%	0.327	0.413	0.214	0.219

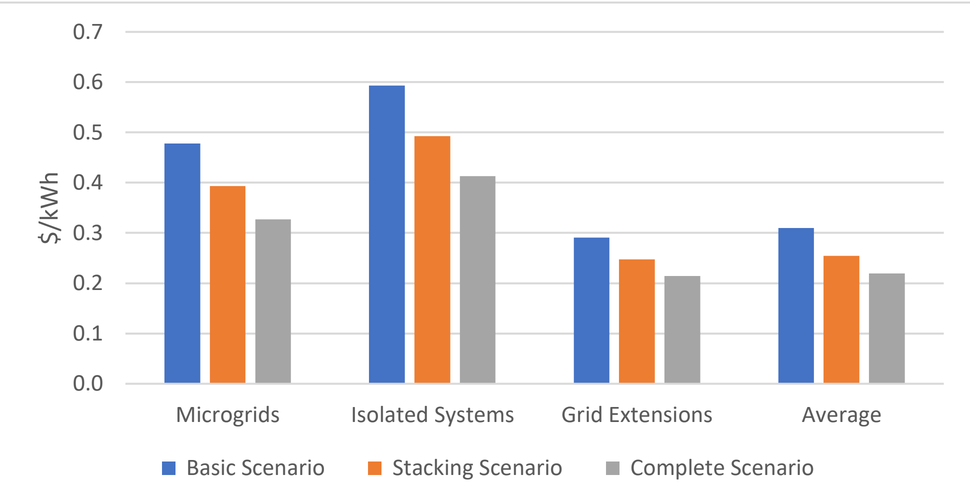

Figure 27. Cost per kWh by electrification mode in the Basic Scenario, Stacking Scenario, and Complete Scenario with microgrids, isolated systems, and grid extensions. Source: own elaboration.

The reduction of electricity cost due to a higher electricity demand is consistent with previous studies (Lee et al., 2019). The reduction of kWh cost in isolated systems is due to the economy of scale in PV systems. The PV equipment for the isolated systems projected by the simulations is: 372 Wp with an initial investment of USD851 for the Basic Scenario; 727 Wp with USD1440 for the Stacking Scenario; and 1,411 Wp with USD2508 for the Complete Scenario. These costs are within the cost range of DC solar kits on the international market (Kit Solaire Discount, 2021).

The demand from grid extension households in Nyagatare is 25,046 MWh/year in the Basic Scenario, 44,382 MWh/year in the Stacking Scenario, and 78,378 MWh/year in the Complete Scenario. If the simulated consumption in Nyagatare District were to be extended to the whole Rwanda, (also assuming the same proportion of grid connections, microgrids and isolated systems), the grid demand would be 1,036,502 MWh/year in the

Basic Scenario, 1,836,729 MWh/year in the Stacking Scenario, and 3,243,642 MWh/year in the Complete Scenario, energy that could not currently be supplied with the country's installed capacity.

Although Rwanda currently has an electricity generation surplus despite an installed capacity of only 150 MW (Government of Rwanda, 2020), this is due to the low rate of connected households and the low consumption per household. Thus, in order to generalize the Basic Scenario, Stacking Scenario, and Complete Scenario to the whole country by 2030, installed generation capacity would have to grow substantially in the coming years.

3.4.2 Household Electricity and Cooking Costs

This section analyses the cost of electric cooking and the competitiveness between cooking with electricity and cooking with LPG, charcoal, and firewood. The breakeven price between electricity and every other fuel is lower for the average grid-connected households, which account for more than 96% of the customers in both the Stacking Scenario and the Complete Scenario. For grid-connected households, the cost of electricity amounts to 153.70 USD/year in the Stacking Scenario and 234.69 USD/year in the Complete Scenario, and additional cooking costs are 47.49 USD/year in the Stacking Scenario and 128.48 USD/year in the Complete Scenario (Table 14 and Figure 28). The cooking cost for grid-connected households is higher than the 27 USD/year national average expenditure for households using firewood (Hakizimana et al., 2020) but not for those using LPG and charcoal.

The LPG breakeven price for an average grid household is 1.05 USD/kg for the Stacking Scenario and 1.37 USD/kg for the Complete Scenario, but the average LPG price in Kigali can reach 1.30 USD/kg (Bishumba, 2021), with higher costs incurred in areas far from distribution networks. The charcoal breakeven price is 0.16 USD/kg for the Stacking Scenario and 0.21 USD/kg for the Complete Scenario, but the average cost in urban areas is between 0.27 and 0.36 USD/kg (Batchelor et al., 2018), with lower prices in rural areas.

The LPG and charcoal breakeven prices are higher for an average microgrid household (between 40% and 43% higher compared to grid households), and much higher for an average isolated system household (between 77% and 81% higher compared to grid households). The price of LPG in isolated areas is higher than in cities due to logistical costs and limited market development, and the economic advantage of cooking with each fuel has to be analysed locally.

Table 14. Annual HH cost for electricity and cooking, breakeven price for LPG, charcoal, and firewood. All values are in US dollars. Source: own elaboration.

	Cost of electricity			Total and Partial Costs of Cooking with Electricity				Breakeven Price		
	Total	For basic serv.	For Cooking	Electricity cost in Basic Sc.	Additional cost*	Appliances cost	Electricity and Appliances cost	LPG	Char-coal	Fire-wood

Grid Ext.	**Stack. Sc.**	153.70	90.41	63.29	106.21	47.49	15.00	62.49	1.05	0.16	0.08
	Comp. Sc.	234.69	78.23	156.46	106.21	128.48	30.00	158.48	1.37	0.21	0.11
Micr.	**Stack. Sc.**	244.11	143.59	100.52	174.43	69.68	15.00	84.68	1.48	0.23	0.10
	Comp. Sc.	358.47	119.49	238.98	174.43	184.04	30.00	214.04	1.92	0.30	0.13
Iso. Syst.	**Stack. Sc.**	305.54	179.73	125.81	216.48	89.06	15.00	104.06	1.86	0.29	0.13
	Comp. Sc.	452.57	150.86	301.71	216.48	236.09	30.00	266.09	2.43	0.38	0.17

* Additional cost refers to the difference in electricity cost compared to the Basic Scenario.

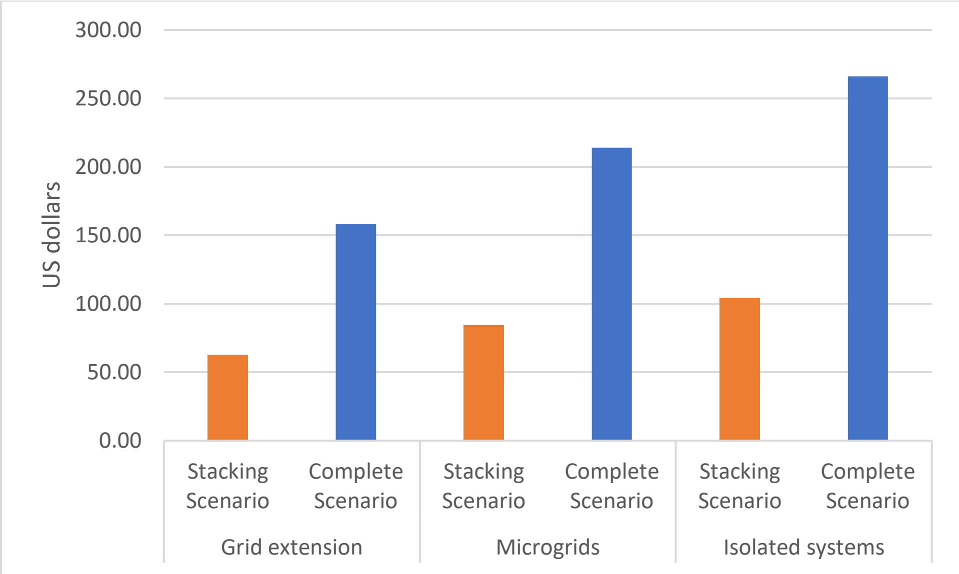

Figure 28. Additional and total costs of cooking with electricity in the Stacking Scenario and Complete Scenario with grid extension, microgrids, and isolated systems. Source: own elaboration.

The results show the competitiveness of cooking with electricity compared to alternatives and are consistent with recent studies (ESMAP, 2020a). The MTF considers that access to electricity or MECS is affordable if it accounts for more than 5% of household expenditure, or 10% for both electricity and MECS. In Rwanda in 2018, the total household consumption expenditure was USD7341 million for 12.302 million people (World Bank, 2021b). Assuming four people per household, the household expenditure was 2387 USD/year per household. The average growth of the GNI per capita was 4.36% in the ten years before 2018, and assuming the same average growth for the forthcoming years, household expenditure would be close to 4000 USD/year per household by 2030. A share of 5% of this amount is 200 USD/year, which is less than the average cost of electricity for basic services in all scenarios, less than the average cooking cost in the Stacking Scenario, and less than the average cooking cost in the Complete Scenario for grid households. However, because household expenditure is not equal in every household, access to either electricity or MECS might not be affordable for low-income households in any scenario in the absence of subsidies.

3.4.3 Total Cost for Electrification of Nyagatare District.

The total cost for the electrification of all Nyagatare customers varies in each scenario. In the Basic Scenario, the total cost per year is USD10,868,613. This amount increases by 27.90% to reach the Stacking Scenario and 82.01% to reach the Complete Scenario.

Cooking with isolated systems increases the cost attributed to household electrification and reduces the cost for non-households and their kWh cost. Due to the displacement of customers from microgrids and isolated systems to grid extension in the Stacking Scenario and the Complete Scenario, the cost of grid extensions increases and the cost of isolated systems decreases in both scenarios. The cost of microgrids decreases in the Stacking Scenario but increases in the Complete Scenario (Table 15).

Table 15. Total annual cost for Nyagatare District electrification for all customers, households, and non-households. Source: own elaboration.

Scenarios	All Customers				Household Customers	Non-HH Customers
	Microg.	Isol. Sys.	Grid Ext.	Total	Total	Total
Basic Sc.	513,662	657,450	9697,502	10,868,613	8406,912	2461,701
Stacking Sc.	407,696	347,214	13,145,682	13,900,591	11,744,338	2156,253
Complete Sc.	733,959	316,966	18,730,646	19,781,572	17,845,445	1936,127

3.4.4 Greenhouse Emissions

The lowest CO_2eq emissions are produced by cooking with electricity and LPG. The lowest emission option is stacking with LPG—414.5 kg/year/HH—followed by cooking only with electricity—449.0 kg/year-HH—and cooking only with LPG—468.5 kg/year-HH (Table 16). In the Nationally Determined Contribution, the Rwandan Government has committed to a low carbon mix of power generation for the national grid, and this action would reduce Complete Scenario emissions to below those of the Basic Scenario and Stacking Scenario with LPG.

Cooking with charcoal and firewood produces much higher emissions. Considering only the final use, charcoal emits less than firewood, but this situation is the opposite if the emissions of charcoal production are considered. In these circumstances, cooking only with charcoal produces 4802.5 kg/year-HH, more than 10 times the emissions when only electricity and/or LPG is used (Figure 29).

The global GHG household emissions derived from cooking in Nyagatare are 356,577 t/year using only charcoal and 200,790 Tn/year using only firewood. These figures are reduced to 191,118 (46.40%) and 113,224 (43.61%) respectively by stacking with electricity.

Table 16. Annual GHG emissions in the Complete Scenario, Basic Scenario, and Stacking Scenario with different fuels. Source: own elaboration.

		Energy consumption			GHG Emissions per HH (kg CO2eq/year)				GHG Em. Nyaga-tare (tCO_2e /year)
		Electricity (kWh/year)	Fuel (kg/year)	% Grid Connected HH	From Electricity	From Fuel	To-tal	Including Charcoal Production	
Elec.	Comp. Sc.	1095.0	-	92.33%	414.5	-	449.0	449.0	33,334
LPG	Basic Sc.	365.0	102.2	96.32%	144.1	318.8	468.5	468.5	34,782
	Stacking Sc.	620.5	51.1	96.2%	244.9	159.4	413.8	413.8	30,725
Charcoal	Basic Sc.	365.0	638.8	96.3%	144.1	1308.4	1452.5	4802.5	356,577
	Stacking Sc.	620.5	319.4	96.2%	244.9	654.2	899.1	2574.0	191,118
Firewood	Basic Sc.	365.0	1277.5	96.3%	144.1	2560.2	2704.3	2704.3	200,790
	Stacking Sc.	620.5	638.8	96.2%	244.9	1280.1	1524.9	1524.9	113,224

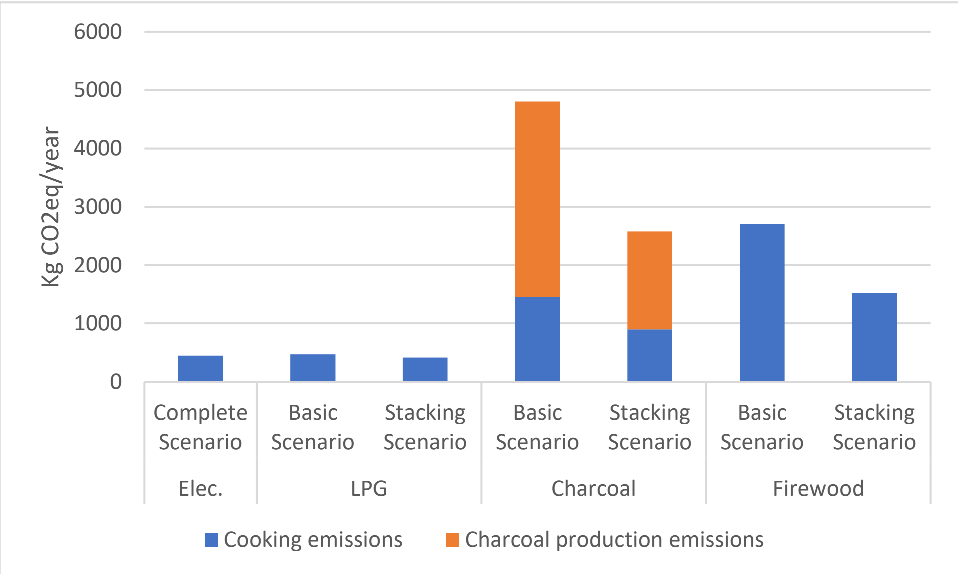

Figure 29. Annual GHG emissions in the Complete Scenario, Basic Scenario, and Stacking Scenario with different fuels. Source: own elaboration.

The results related to the reduction in GHG emissions by replacing biomass with electricity or LPG for cooking are consistent with those of the modern fuel and electric cooking scenarios in Sub-Saharan Africa developed by (Dagnachew et al., 2020).

Due to the use of wood in charcoal production, cooking with charcoal is the most wood-demanding alternative, needing more than 3 Tn/year-HH in the Basic Scenario and 1.5 Tn/year-HH in the Stacking Scenario. Assuming a factor of non-renewable biomass of 58.45%, cooking only with charcoal in Nyagatare produces a loss of 138,602 Tn/year of biomass, whereas stacking with electricity reduces this amount by half, and cooking with electricity and/or LPG eliminates the loss (Table 17).

Table 17. Wood and non-renewable biomass consumption from firewood and charcoal production. Source: own elaboration.

		Wood Consumption		Non-Renewable Biomass	
		Per HH (Kg/year)	For Nyagatare (t/year)	Per HH (Kg/year)	For Nyagatare (t/year)
Charcoal	Basic Sc.	3193.8	1866.7	237,129.6	138,602
	Stacking Sc.	1596.9	933.4	118,564.8	69,301
Firewood	Basic Sc.	1277.5	746.7	94,851.8	55,441
	Stacking Sc.	638.8	373.3	47,425.9	27,720

One of the measures planned by the Government of Rwanda in its Nationally Determined Contributions is to reduce firewood and fossil energy consumption for cooking to mitigate GHG emissions. Stacking Scenario and Complete Scenario emissions show that replacing firewood and charcoal with LPG is an effective means of achieving this target, and electricity replacement may also be effective in the future if there is a lower carbon mix of power generation for the national grid.

3.4.5 Sensitivity Analysis

Change in wholesale energy costs leads to a change in electrification modes, particularly the swapping between grid extensions and microgrids. Higher wholesale energy cost results in fewer grid extensions, and more microgrids and isolated systems (Table 18).

A 3.0 cents/kWh difference in wholesale energy cost is passed on to the average kWh cost for customers with an impact of about 3.0 to 3.2 cents/kWh. The kWh cost increases in grids between 2.3 and 2.9 cents, reduces in microgrids between 0.2 and 2.5 cents/kWh, and remains the same in isolated systems. The high kWh cost in microgrids together with an increase in their proportion leads to a rise in average kWh cost, which is higher than the cost to customers connected to grids.

When the wholesale energy cost decreases by 3.0 cents, the average cost is reduced by 3.2 cents in all scenarios. The kWh cost reduces in grids by between 2.4 and 3.1 cents/kWh, varies slightly upwards or downwards in microgrids, and remains the same in isolated systems. The reduction in the proportion of microgrids, which have a higher kWh cost, leads to a reduction that is slightly in excess of 3.0 cents/kWh.

The variation of kWh cost due to the variation of wholesale energy cost lies between 29.17% and 44.45% throughout all the electrification modes, between 24.74% and 40.59% for grids, between 0.58% and -14.82% for microgrids, and nil for isolated systems.

Table 18. Fraction of households and kWh cost for microgrids, isolated systems, and grid extensions, for a wholesale energy cost of 0.09 USD/kWh, 0.12 USD/kWh and 0.06 USD/kWh. Source: own elaboration.

Scenario	Wholesale energy cost	Fraction of households			kWh cost (USD)			
	$/kWh	Microg.	Isol. Sys.	Grid Ext.	Microg.	Isol. Sys.	Grid Ext.	Average
Basic Sc.	0.09	3.66%	4.01%	92.33%	0.478	0.597	0.291	0.310
	0.12	8.20%	4.94%	86.86%	0.453	0.597	0.315	0.340
	0.06	1.19%	2.56%	96.25%	0.479	0.597	0.267	0.278
Stacking Sc.	0.09	2.21%	1.54%	96.25%	0.393	0.494	0.248	0.255
	0.12	7.96%	2.95%	89.09%	0.387	0.494	0.271	0.287
	0.06	1.70%	1.23%	97.07%	0.393	0.494	0.217	0.223
Complete Sc.	0.09	2.74%	0.94%	96.32%	0.327	0.409	0.214	0.219
	0.12	7.07%	1.55%	91.38%	0.326	0.409	0.243	0.252
	0.06	0.83%	0.39%	98.78%	0.338	0.409	0.185	0.187

Reductions of 10% and 20% in the cost of PV equipment lead to a notable change in the percentages of electrification modes, resulting in lower cost of PV equipment, fewer grid extensions, and more microgrids and isolated systems. The reduction in PV equipment cost leads to a reduction in the kWh cost in all electrification modes and scenarios (Figure 30). However, the average kWh cost changes insignificantly, by no more than 0.2 cents of a dollar, because the reduction of kWh costs is compensated by a higher fraction of microgrids and isolated systems, which means higher kWh costs and a high fraction of households with grid extension (Table 19). The sensitivity of average kWh cost versus PV equipment cost is less than 3%.

The greater the PV equipment cost reduction, the higher the kWh cost reduction for each individual electrification mode. The largest reductions are off-grid systems, which reduce the cost of electric cooking and the breakeven price of LPG and charcoal in these settings.

Table 19. Fraction of households and kWh cost for microgrids, isolated systems and grid extension, for a PV equipment cost reduction of 10% and 20%. Source: own elaboration.

	ER cost reduction	Fraction of Customers			HH's Total Cost Per kWh (USD/kWh)			
	%	Microg.	Isol. Sys.	Grid Ext.	Microg.	Isol. Sys.	Grid Ext.	Aver.
Basic Sc.	0%	3.66%	4.01%	92.33%	0.478	0.597	0.291	0.310
	−10%	6.26%	5.06%	88.68%	0.449	0.561	0.284	0.308
	−20%	16.82%	6.93%	76.25%	0.394	0.532	0.270	0.309
Stacking Sc.	0%	2.21%	1.54%	96.25%	0.393	0.494	0.248	0.255
	−10%	6.51%	2.72%	90.77%	0.367	0.461	0.241	0.255
	−20%	13.29%	3.91%	82.80%	0.331	0.430	0.233	0.254
Complete Sc.	0%	2.74%	0.94%	96.32%	0.327	0.409	0.214	0.219
	−10%	3.72%	1.14%	95.15%	0.307	0.387	0.213	0.219
	−20%	10.32%	1.95%	87.74%	0.278	0.356	0.207	0.217

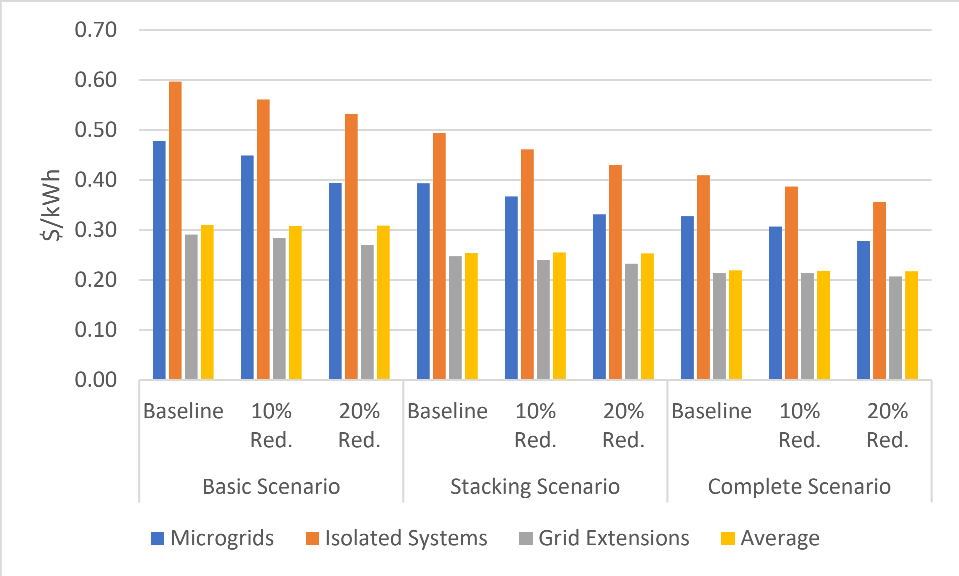

Figure 30. kWh cost for microgrids, isolated systems and grid extensions, for a PV equipment cost reduction of 10% and 20%. Source: own elaboration.

In the Basic Scenario, using the National Electrification Plan basic consumption instead of 1 kWh/day demand, the average kWh cost increases by USD0.50, from USD0.310 to USD0.810, with a change in the proportion on electrification modes (Figure 31 and Table 20). This is due to the increase in the kWh cost in all electrification modes and the increased proportion of the most expensive modes (microgrids and isolated systems). The average kWh cost increases less in the Stacking Scenario— USD0.104—and the Complete Scenario— USD0.039.

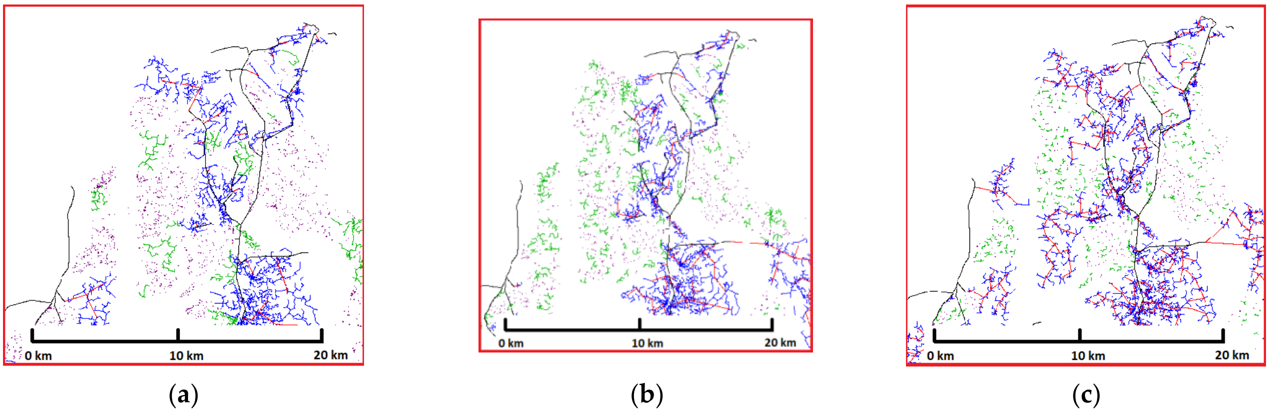

Figure 31. Distribution of grid extensions (blue), microgrids (green), and isolated systems (red dots) in the Basic Scenario (a), Stacking Scenario (b), and Complete Scenario (c) with National Electrification Plan basic consumption. Source: own elaboration.

Table 20. Fraction of households and cost per kWh by electrification mode in the Basic Scenario, Stacking Scenario, and Complete Scenario with a basic consumption of 1 kWh and using the NEP basic consumption. Source: own elaboration.

	Basic Pack.	Fraction of Customers			HH Total Cost Per kWh (USD/kWh)			
		Microgrids	Isolated Systems	Grid Extensions	Microgrids	Isolated Systems	Grid Extensions	Average
Basic Sc.	1 kWh	3.66%	4.01%	92.33%	0.478	0.593	0.291	0.310
	NEP	13.96%	8.93%	77.11%	0.959	2.823	0.550	0.810
Stacking Sc.	1 kWh	2.21%	1.54%	96.25%	0.393	0.492	0.248	0.255
	NEP	12.38%	4.15%	83.47%	0.505	0.765	0.318	0.359
Complete Sc.	1 kWh	2.74%	0.94%	96.32%	0.327	0.413	0.214	0.219
	NEP	4.47%	1.43%	94.10%	0.372	0.486	0.249	0.258

The electricity available with the National Electrification Plan basic consumption is 50 Wh/day or 450 Wh/day, 20- or 2.2-fold less than that available with 1 kWh, respectively; however, the savings with the National Electrification Plan consumption are relatively low. For household customers the saving is 2,790,648 USD/year or 37.55 USD/year-HH in the Basic Scenario; 2,493,955 USD/year or 33.56 USD/year-HH in the Stacking Scenario; and 2,218,613 USD/year or 29.85 USD/year-HH in the Complete Scenario (Table 21). Given the benefits of having Tier 3 electricity access, as opposed to Tier 1 or 2, and the limited savings with the National Electrification Plan basic consumption, planning electricity access with the 1 kWh basic consumption appears worthwhile.

Table 21. Total annual cost for Nyagatare District electrification for all customers, households, and non-households with a basic consumption of 1 kWh and using the National Electrification Plan basic consumption. Source: own elaboration.

	Basic consumption	Microgrids	Isolated Systems	Grid Extensions	Total	Household Customers	Non-HH Customers
Basic Sc.	1 kWh	513,662	657,450	9,697,502	10,868,613	8,406,912	2,461,701
	NEP	904,282	1,045,292	6,128,391	8,077,965	4,512,670	3,565,295
Stacking Sc.	1 kWh	407,696	347,214	13,145,682	13,900,591	11,744,338	2,156,253
	NEP	1,596,983	731,233	9,078,421	11,406,636	8,825,401	2,581,235
Complete Sc.	1 kWh	733,959	316,966	18,730,646	19,781,572	17,845,445	1,936,127
	NEP	996,180	417,405	16,149,374	17,562,959	15,446,649	2,116,310

3.4.6 Caveats and Ongoing Future Research

This work is a first approximation towards developing and testing a methodology for the introduction of electric cooking in large-scale electricity planning in areas without electricity. Extrapolating the results obtained in the Nyagatare District case study to other regions must be carried out with caution.

Due to the lack of reliable data, it was necessary to make certain assumptions about household demand profiles, both for electricity and cooking fuel consumption, and about equipment costs. The costs by 2030 will depend on technological developments and government policies in the coming years. With other values, the results may vary, but the methodology remains valid, nevertheless.

In this study, it was considered that the generation capacity of the grid can reliably meet the demand, including peak demand. However, this may not be the case if demand growth is faster than supply growth. Estimations of greenhouse gas emissions did not consider the life cycle of fuels and electricity due to lack of information and are therefore underestimated.

The analysis in this study relied on a solid computer-based model of electricity supply. However, a similar model for the fuels that compete with electricity and the associated demand needs further development.

On the cooking fuel supply side, a georeferenced layer with LPG, charcoal, and firewood distribution networks must be developed in addition to the estimation of the fuel costs at the household level, hotspots of deforestation and charcoal production, availability and cost of stoves and electric cooking equipment, government policy priorities, public subsidy options, and the plans of business and civil society.

On the demand side, additional information must be gathered for each household: cultural preferences, electricity and fuels demand profile, prioritized technologies for stacking, ability and willingness to pay, household expenditure, health impacts, and time for collecting free firewood.

With these two layers of georeferenced data, it will be possible to match the supply and demand sides to establish the least-cost solution based on social, environmental, and political criteria (even in the absence of e-cooking).

3.5 Conclusions

This study lays the foundations for the integration of electric cooking and MECS in the electrification planning of unserved areas. The approach has been illustrated by its application to Nyagatare District in Rwanda.

The methodology developed is useful for planning the electrification of unserved regions considering the use of electricity for cooking, although some aspects must still be improved, and some assumptions must be removed; calibration of the model for a particular region allows the analysis of multiple situations and scenarios.

In the Nyagatare District case study, the hypothetical penetration of electric cooking would substantially change the fraction of households electrified with each electrification mode in the least cost plan and would lead to a reduction in the kWh cost, both for households and for all consumers as a whole.

Electric cooking can be cost-competitive compared to LPG for grid-connected households, but not for non-grid-connected households. Its competitiveness with charcoal will depend on the future cost of this fuel in rural areas. Replacing firewood and charcoal with electricity for cooking is an effective means to achieve GHG emission reductions.

Clean stacking with electricity significantly reduces kWh cost and the need for collection of non-renewable biomass, with a limited increase in global cost for electrification and cooking. Therefore, this scenario is a transitional means to meet MECS.

4. MEASURES TO PROMOTE ELECTRIC COOKING

Research question: **What measures can facilitate the eCooking transition?**

Some of the ideas presented in this chapter have been discussed within the Africa-Europe High-Level Platform for Sustainable Energy Investments in Africa (July-October 2019), the project "Models and scenarios for mass deployment of electric cookstoves to promote sustainable energy access in low- and middle-income countries", funded by the Fundación Iberdrola (September 2019-July 2020), and the working group for the elaboration of the report “SDG 7 in Ibero-America. Reaching the last mile. Affordable, safe, sustainable and modern energy for all” (SEGIB et al., 2021).

In order to have a broad view of all factors and their context, factors that have influenced other processes of cooking transition have been identified, and then analysed against the eCooking perspective.

4.1 Review of factors influencing cooking transition

(Puzzolo et al., 2016) made a systematic review of the literature to identify the barriers and enablers for the adoption and sustained use of clean fuels, namely, liquefied petroleum gas (LPG), biogas, solar cooking and alcohol fuels, in low- and middle-income countries. Drawing on this work, (Rosenthal et al., 2018) developed a basic logic model to aid the planning and evaluation of LPG cooking programs with health endpoints. Quinn et al. (2018) adapted and generalized the logic model to gas stoves, alcohol, electricity, and biomass stove/fuel combinations that meet the ISO Tier-4 standard for emissions to elaborate the generalized logic model for clean fuel scale-up, with 33 factors grouped in five main categories of interlinked influences: enabling environment; industry structure and services; energy pricing and costing; factors influencing consumer demand; and user and community needs and perceptions.

From a supply and demand perspective, Putti et al. (2015) identified the major barriers affecting the clean cooking appliance ecosystem, highlighting some factors different from those of GLM, such as culturally appropriate design, lack of consumer/market intelligence, sector coordination, program monitoring and impact assessment.

Later, (ESMAP, 2021) made a systematic review of 91 evidence-based articles on demand- and supply-side drivers and barriers to transition to MECS, highlighting the relationship between the individual and their environment (Figure 32). Most of the factors identified are within the GLM, but others are different, like peer influence and trust in the information source, or competition with existing fuels and technologies in a comprehensive way, not only from pricing perspectives, including low incentive to change.

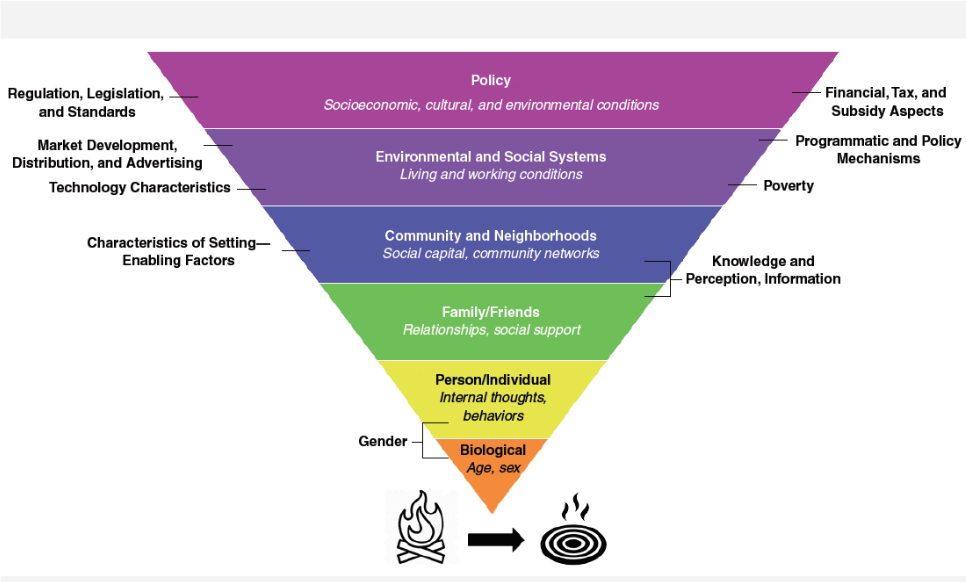

Figure 32. Modified Dahlgren-Whitehead model of relationships between an individual and her environment. Source: ESMAP, 2021.

ESMAP (2020e:95) made some specific recommendations for enabling eCooking as a mainstream solution in LMIC, which included establishing links between the clean cooking sector and the electric sector; supporting research to obtain evidence; supporting the private sector to target the needs and aspirations of groups with fewer resources; and helping consumers understand the advantages of eCooking.

From their considerable experience of promoting ICS, (Ruiz-Mercado & Masera, 2015) identified three stages in the adoption process of new stoves and fuels: acceptance, initial use and sustained use. There are different factors influencing each stage. For example, Rehfuess et al. (2014) identified 31 factors associated with the first two stages, those of acceptance and initial use. These factors were influential depending on the context; they could not be ranked by the degree of importance; and none could be specifically associated with the exclusive or near-exclusive third stage, that of use of the stoves. Some factors not previously mentioned are household ownership and structure, climate, market development, demand creation, supply chains, business and sales approach, and community involvement.

Factors related to sustained use were identified by Zamora (2011) in Central Mexico, highlighting socioeconomic factors: income and education; socioecological factors: level of access to gathering fuel and climate conditions; technological factors: use of LPG and use of multiple fuels and stoves for cooking; and cultural factors: attachment to ancestral ways of cooking and the use of traditional pots.

Matin & Roe (2016) made a literature review from a social perspective with a view to identifying the approaches that drive towards a most effective individual and household behaviour change. The most used strategy has been rewards, such as financial incentives, fuel costs and availability, subsidies, credit or delivering cookstoves free of charge. However, recent studies and grey literature have highlighted the importance of shaping knowledge and social support:

Matin & Roe (2016) highlight other factors not covered in previous models, such as governance framework, presence of NGOs, local administrative capacities, health and welfare services, educational resources, discriminatory structures, social norms and values, social capital and neighbourhood cohesion, psychological capabilities (motivation agency belief, personality, values, attitudes, beliefs), physical capabilities (skills, mobility, health), and demographics (ethnicity, occupation).

Batchelor et al. (2019) studied the narratives on cleaner cooking solutions, differentiating between the old narrative, whose key drivers were environment, health, economics and gender issues, and the new narrative, whose key drivers must be aspiration for modernisation, demographics, electrification, and the economic advantages of MECS.

Steven (2007), cited by Batchelor (2019), gives some guidance for influencing policy, which will be taken into consideration.

Finally, taking into account the preceding contributions, it has been concluded that the factors identified can be grouped into 3 categories, as shown in 33. Some factors are closely related; for example, regulation influences the behaviour of the industry, which in turn influences the price of fuels, while subsidies directly affect affordability. Other factors are contextual, which assume that the same factor can facilitate the transition in one context and hinder it in another, so they must be interpreted in each specific situation (ESMAP, 2021b).

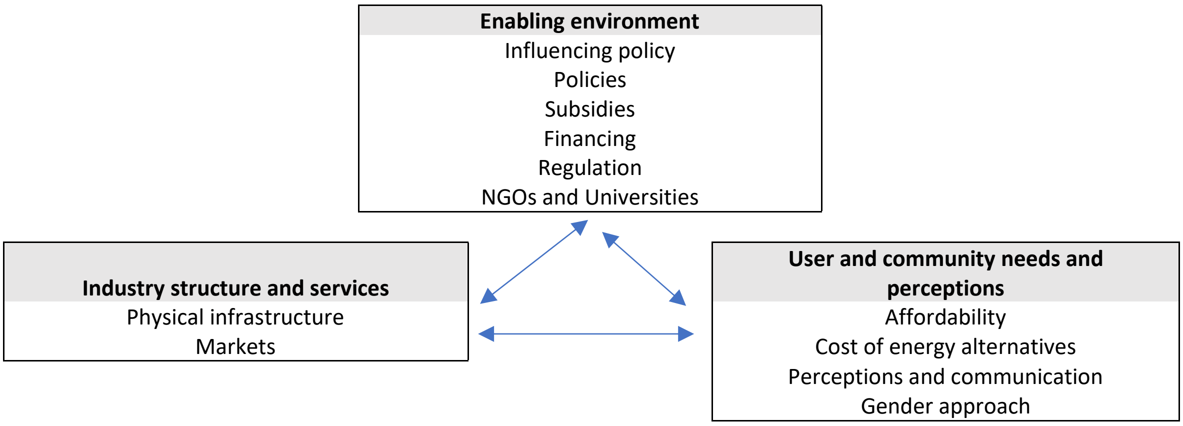

Figure 33. Main factors influencing eCooking transition. Source: own elaboration.

4.2 Enabling environment

4.2.1 Influencing policy

Steven (2007, cited by Batchelor, 2019) proposes the following lines of action to influence policies:

- Changing perceptions and public opinion.

- Setting an agenda by reframing the way an issue is debated.
- Building networks.
- Developing capacity within organisations.
- Changing institutions.

Narratives

Until now, the most widespread narrative is that eCooking is only feasible for affluent countries and for people in urban areas (Smith et al., 2014), partly because the actual costs are not known and eCooking is assumed to mean cooking exclusively with electricity. On the other hand it must be acknowledged that, cooking with energy-efficient electric appliances supplied with clean electricity is the most direct means of meeting the three targets of SDG 7 (universal access, efficiency, and renewable energy) and thus contributing towards complying with the Paris Agreement. In the context of climate change and movement towards a carbon neutral economy, the new narrative must be that "eCooking is an inevitable option", and the sooner it becomes widespread, the better for people and the planet.

It is also important to change the narrative about stacking, so that it is seen not just as a problem but rather as an important part of the transition to MECS (ESMAP, 2020b).

These two main ideas can be complemented by others to update the old narrative (Batchelor, 2019):

- Modernisation aspiration: women, in particular the youngest ones, aspire to convenience and clean systems that can be satisfied with eCooking.
- Demographics: the percentage of urban population is increasing, with better access to electricity, higher income, and a greater tendency to use eCooking.
- Economics: the price of eCooking, especially efficient eCooking, is in many contexts lower than alternatives.
- Electrification: access to electricity is advancing much faster than access to MECS, and investments in the electricity sector are much greater than in the cooking sector, so it is important to associate MECS with electrification.

Recommendation 1. To spread the narrative that, in the context of climate change and the movement towards a carbon neutral economy, eCooking is an inevitable option, and stacking is a fundamental part of the transition process.

Recommendation 2. To contrast the arguments against eCooking with the arguments for modernization aspiration, demographics, economics, and electrification.

Building networks

In the clean cooking sector, there are more than 2,000 entities working (CCA, 2021b). Furthermore, there are important networks, such as the Clean Cooking Alliance, which organizes every two years the Clean Cooking Forum, which serves as a meeting space for the sector. However, in this space most entities work on the promotion of ICS and LPG, so they are unlikely to lead the transition to eCooking.

The LPG sector has a network for the promotion of this fuel in cooking, led mainly by the World LPG Association (WLPGA, 2021), and the Global LPG Partnership (GLPGP, 2021), which has as its mission "To assist developing countries to plan, finance and implement national-scale availability and use of liquefied petroleum gas (LPG and bio-LPG)". The GLPGP carries out effective work in research, dissemination and lobbying, establishing links with the gas industry of each country.

There is no organizational equivalent to GLPGP for the promotion of eCooking. Electricity companies can play a major role in a wide alliance because households that can cook with electricity will be their customers and will provide revenue in the long term, so the utilities will be clear beneficiaries. Because of the implications of the eCooking transition, existing networks related to gender and energy can be an important player in an eCooking network, such as the International Network on Gender and Sustainable Energy.

Recommendation 3. To establish an alliance to promote eCooking and assist LMIC to plan, finance and implement eCooking transition on a national scale.

Awareness-raising and training

For most, clean cooking is an invisible question. In the electricity sector, the problem of lack of access to modern energy for cooking worldwide and the important contribution that the sector can make to alleviate this problem are practically unknown. In academic study programs, modules that address this issue, like universal access to energy, can be included. This is already being done in the Master's Program in Renewable Energies and Environment from the Polytechnic University of Madrid (UPM, 2021) or the Florence School of Regulation. For professionals who are outside the formal educational spaces, this can be reached through professional media.

Publications, seminars, and specific studies can be used to raise awareness and train those responsible for energy planning.

Recommendation 4. To raise awareness among professionals in the electricity sector and energy planners about eCooking opportunities.

4.2.2 Policies

Access to energy is not implicitly recognized as a human right. However, to the extent that it is necessary to guarantee other human rights, such as the right to health, the right to decent housing, the right to development, or non-discrimination, it can be addressed by the Human Rights-Based Approach (UNSDG, 2021), in which States have an obligation to respect, protect and fulfil such Access (OHCHR, 2021).

Despite the fact that the first recommendation made by the multi-stakeholder SDG 7 Technical Advisory Group at UN High-Level Political Forum was "make clean cooking solutions a top political priority", this is far from happening (UNDESA, 2018). Zhang (2021) points to the lack of prioritization at all levels, including national governments, the private sector, donors and households. She considers clean cooking as an "orphan sector".

International policy

International institutions, such as the International Energy Agency, the World Bank, or the European Union, have a great influence in shaping the energy discourse and policies of LMIC, so they must be the first to change their view of eCooking.

Recommendation 5. To review the international discourse on eCooking and include it as a basic electricity service.

National Commitment

Unlike for target 7.1.1., in the case of target 7.1.2 for access to MECS, there is no equivalent commitment in many countries. A formal commitment at the highest level must be the first step in guiding long-term policies. It would be appropriate for the commitment not only to be a political declaration but to be included in a law passed by parliament so that it would be safe from changes in government and could be enforced through the legal system.

The commitment should establish a level of access in MTF's Tier 4 or 5, 100% of the population in the country, the final deadline, and a schedule of intermediate goals. Electricity should be cited in the declaration as one of the means of meeting this objective. A national commitment would make it possible to achieve greater economies of scale and high-level coordination of different policies.

The COVID-19 pandemic has profoundly disrupted all human activity since February 2020. The impact on the energy sector has been more significant than that produced by any recent event; its effects will last for years and may undermine the ongoing energy transition (IEA, 2020c). Vulnerability to COVID-19 has been greater in rural and peri-urban populations that use firewood for cooking (O. Masera et al., 2020), highlighting the need for recovery plans that focus on an integrated response in order to enable access to modern energy cooking in low- and middle-income countries (Batchelor & Brown, 2020). The COVID-19 recovery plans would do well to include the impulse to eCooking.

Recommendation 6. To establish at national level a commitment to reach MTF's Tier 4 and 5 with a specific mention to eCooking.

Recommendation 7. To use the COVID-19 recovery plans to impulse eCooking.

Energy planning

The political commitment must be reflected in the integration of cooking energy demand into national energy policy. As seen in Chapter 3, the inclusion of eCooking changes electrification planning and the boundaries between the modes of electrification, and reduces the cost of kWh. In the case of microgrids, an eCooking study in Haiti shows a substantial change in the demand profile, while the saving in charcoal of users who used eCooking opened new opportunities for the financing of microgrids (Bilich, 2020).

Most surveys on energy cooking systems only cover primary fuels, which gives a limited picture of the situation and little information on eCooking when used as a supplementary resource. Similarly, the characteristics of the cooking space are not accurately depicted, which makes it difficult to estimate HAP concentration and health impacts.

Recommendation 8. To include the eCooking demand when planning the electricity scenarios.

Recommendation 9. In surveys on cooking systems, to measure the utilization of all cooking systems and the conditions of the cooking space.

Climate change policy

Many countries' emission inventories do not disaggregate cooking emissions by fuels and electricity, and biomass is considered carbon neutral, when it is not. Nor are emissions from short-lived pollutants indicated. Cooking with electricity and its potential for GHG and short-lived pollutant reduction are not included in the future scenarios.

Recommendation 10. In national emissions inventories, future emissions scenarios and NDCs, to break down emissions from cooking by fuels and electricity, specifying CO2eq emissions and short-lived pollutants.

Environmental policy

In most countries, the LCA of the different combinations of fuel-stoves or electricity-appliances used for cooking are not known, making it difficult to compare their environmental impacts. However, it is known that charcoal has a considerable environmental impact, and there are already countries that have plans to reduce its use.

Recommendation 11. To make and publish LCA for different combinations of fuel-stove or electricity-appliances for cooking.

Recommendation 12. To establish plans to diminish charcoal consumption.

Health Policy

Although IHME calculates the HAP-attributable burden for every country each year, these calculations are based on the assumptions of PM2.5 concentrations, which are quite inaccurate, so it is advisable to have reliable data to know the magnitude of the problem.

Even in many households where clean solutions are available and affordable, they are still using "dirty" practices (ESMAP, 2021). The population should be aware of the health risk posed by exposure to HAP and how to avoid it. In order to raise awareness amongst the population, many measures can be carried out: working with school children within the education system, training for health personnel and health promoters, mass communication campaigns through radio and television, etc.

Recommendation 13. To accurately calculate the HAP-attributable health burden impacts.

Recommendation 14. To raise public awareness of the health risks of HAP, their associated costs, and how to avoid exposure.

Institutional Leadership

Strong institutional leadership is needed to drive and coordinate the transition to MECS. ESMAP (2020a) proposes the creation of an inter-ministerial space to develop a single investment strategy, and a space for dialogue between the clean cooking sector and the electricity sector.

Although MECS affect multiple policies and ministries, the energy dimension is the most important area. Energy ministries, regulators, and in many cases public companies, have capacities and resources to manage major initiatives such as the transition to MECS. Having already competence over the electricity sector and LPG, they are in the best position to promote their use in eCooking.

Recommendation 15. To establish the political and operational direction of MECS transition in the Ministry of Energy.

Cooking transition programmes

In specific cooking transition programmes, a pre-feasibility study of eCooking must be done in order to gauge its potential. The case of The Indian Himalayas (Pattanayak et al., 2019) showed that when households were given a choice between electric stove and ICS biomass (both subsidized), the demand for electric stoves was twice as high as that for ICS, demonstrating that in certain contexts, when given the choice, eCooking may be the preferred option.

Lack of awareness of promotion programmes and energy subsidies hinders their adoption. For example, in El Salvador, LPG subsidies were poorly received by poorer users with little information, even though it benefited them. In Peru, lack of awareness of the LPG subsidy delayed its use, while in Nepal, a misunderstanding of the protocol for purchasing subsidized fuel meant that it was purchased infrequently (ESMAP, 2021b). In the case of Nepal, Robinson et al. (2021) show the need for improved communication between all stakeholders. Very clear rules and simple procedure must be established in the programmes so that they can be understood by less-educated people.

Recommendation 16. To do pre-feasibility studies of eCooking in the cooking transition programmes, and give several technological options, including eCooking appliances.

Recommendation 17. To foment communication between all the stakeholders involved in cooking programmes.

4.2.3 Subsidies

There is a shortfall between what MECS costs and what some households can afford. The magnitude of this gap means that only the States have the capacity to cover it, and in many countries, this is already being done through LPG subsidies.

Subsidies can be generalized or focused on groups with fewer resources, linked to the situation of households or equal for all households, intended for the purchase of cooking equipment or fuels/electricity, temporary or permanent, differentiated by technology or technologically neutral, with a system of tariff cross-subsidisation or taxes, etc. Each context requires a specific system of subsidies and ESMAP (2021) points to the need to investigate in depth the role they can play in the MECS transition, especially the subsidies that are maintained in the long term and their possible negative effects. In any case, given that subsidies can account for a large amount of public expenditure, and that generalized subsidies are more used by higher-income households than by low-income households (Das, 2021), subsidies must be designed with a pro-poor approach, and unless there are well-justified cases, subsidies must be targeted at the population with fewer resources.

Recommendation 18. Governments must understand that subsidies are essential to fill the gap between the cost of MECS and the capacity to pay of low-income households, and subsidies should be targeted to these households.

Electricity subsidies

Subsidies are not common for wood and charcoal, but they are usual for electricity and LPG. In general, the lower the electricity tariff, the greater the electricity demand there is for cooking. In South Africa, where the initial quantity of kWh used is free of charge, the use of electricity for cooking is widespread (Kimemia, 2016). In Himachal Pradesh (India), with a lifeline tariff of USD0.016 for the initial 40 kWh/month, and USD0.05 for 250 kWh/month, there has been a good acceptance of eCooking (Banerjee, 2016). In Ethiopia, which also charges a very low price for electricity, the percentage of urban households cooking with electricity increased from 3% in 2011 to 23% in 2016 (IEA, 2019a). In Zambia, with a lifeline tariff of UDS0.014/kWh for the first 200 kWh, eCooking is cheaper than LPG or charcoal (Leach, 2021). In Himachal Pradesh (India), for 60% of the irregular users, the most prominent reason for not using induction stoves regularly was the fear of higher electricity bills (Banerjee et al., 2016).

It is neither simple nor cheap to know how much of the electricity consumption is derived from each cooking appliance, or whether the electricity is being used for cooking or not, and therefore to link electricity subsidies to the use of eCooking; therefore, a lifeline tariff is the simplest instrument to promote both electricity access and eCooking.

The establishment of an affordable lifeline tariff has the enormous advantage of enabling States to fulfil their "obligation", to provide the means to take positive actions to enjoy energy access. ESMAP (2020a) recommends that countries that have a lifeline tariff of more than 0.1 USD/kWh establish at least for the first 100 kWh/month a price of 0.1 USD/kWh or below, the threshold to permit poorer households eCooking to adopt cost-effectively.

In some cases, the existing lifeline tariff would already allow the introduction of eCooking. For example, Tanzania has a lifeline tariff of around 0.04USD/kWh for the first 75 kWh/month, and low-income households have a non-cooking consumption of 30 kWh/month, so they still have the opportunity for eCooking within the lifeline tariff (Scott & Coley, 2021).

The rule "the lower the electric tariff, the higher the penetration of eCooking" may not apply when there are barriers to accessing the tariff or if the fuels that are commonly used are affordable. For example, the Ecuadorian Efficient Cooking Programme (PEC in its Spanish acronym) tried replacing the LPG stove with electric induction stoves, and they gave 80 kWh/month free for cooking, but they did not have the expected success. The initial target was 3.5 million households, but they only reached 740,000. One of the main barriers was that it required the purchase of an induction cooker, which cost around USD500, and although the purchase was subsidized, it meant a high expense for families of low income, and the type of stove had a very low level of acceptance. It follows from the Ecuadorian experience that care must be taken when mandating conditions for eCooking tariffs, and that the initial costs of acquiring the equipment must be taken into account. Furthermore, LPG, which is the technology to be replaced, is heavily subsidized in Ecuador, and the majority of the population were highly satisfied with the use of LPG stoves (Gould et al., 2018).

Where it is possible to differentiate between users, the kWh cost should be inversely proportional to the household income, and the amount directly proportional to the number of people who live in the household. For households that do not yet have electricity, the connection fee can be a deterrent for eCooking. In order to facilitate eCooking, the connection fee must be affordable for all income groups. This measure also facilitates universal access for electricity.

Recommendation 19. To establish a lifeline tariff with the lowest possible price for low-income households to supply non-cooking and cooking services.

Recommendation 20. To establish a very low or free electricity connection fee for low-income households.

LPG subsidies

Based on the analysis of countries accounting for more than three quarters of LPG consumption, the average subsidisation rate for LPG is estimated to be around 40% (IEA, 2014); for example, Ecuador spent USD 711 million subsiding LPG in 2012 (MERNNR, 2020). Once a high LPG subsidy is introduced, there is resistance to its removal by the population. LPG subsidy can be universal for all customers, or focused on the lowest income households, for example for one or two cylinders per household and month, as in Peru.

There is a growing tendency to apply limits to fossil fuel subsidies. For example, SDG target 12.c –to ensure sustainable consumption and production patterns- seeks to "Rationalize inefficient fossil-fuel subsidies that encourage wasteful consumption by removing market distortions, in accordance with national circumstances, including by restructuring taxation and phasing out those harmful subsidies, where they exist, to reflect their environmental impacts, taking fully into account the specific needs and conditions of developing countries and minimizing the possible adverse impacts on their development in a manner that protects the poor and the affected communities". The indicator for this target is ‘Amount of fossil fuel subsidies per unit of GDP (production and consumption) (UN General Assembly, 2015). In most cases, subsidising LPG for cooking does not encourage wasteful consumption, but it can distort the market against the use of electricity for cooking, as has happened in Ecuador.

Recommendation 21. To avoid establishing high subsidies to LPG.

Recommendation 22. To shift subsidies from LPG to electricity, specially to promote access to electricity, eCooking and renewable energy.

Tax import exemption

In countries that do not have the industry to produce eCooking appliances and must import them, import tariffs can account for a significant part of the cost, whereby reductions in import tariffs can be established for the most efficient equipment.

Recommendation 23. To reduce import tariffs for the most efficient cooking equipment.

4.2.4 Financing

IEA (2021) estimates that in order to achive clean cooking by 2030, a cost of US$6 billion must be incurred each year in low-income countries, and ESMAP (2020b) increases this figure up to USD148-156 billion to meet MECS in all countries. However, SEforAll (2020) estimates that in the 20 countries with the largest deficits (High Impact Countries), only USD 131.5 million has been invested in specific programs in 2018, indicating that other sources of funding need to be mobilized. On the other hand, financing in the 20 countries with the largest electricity deficits was USD43,583 million, in the same year (SEforALL, 2020), more than 300 times the figure of clean cooking, so promoting eCooking can benefit from investments in the electricity sector.

Analysis of investment flows in clean Cooking (Figure 34) shows that the investment in eCooking was insignificant (USD0.4 out of USD131.5), 10 times less than investment in Solar Cooking, a technology with very limited potential, or 77 times less than investment in biogas digesters, a niche technology. Furthermore, only 15% of the investment went to Tier 5 systems and 26.5% to Tier 4 systems.

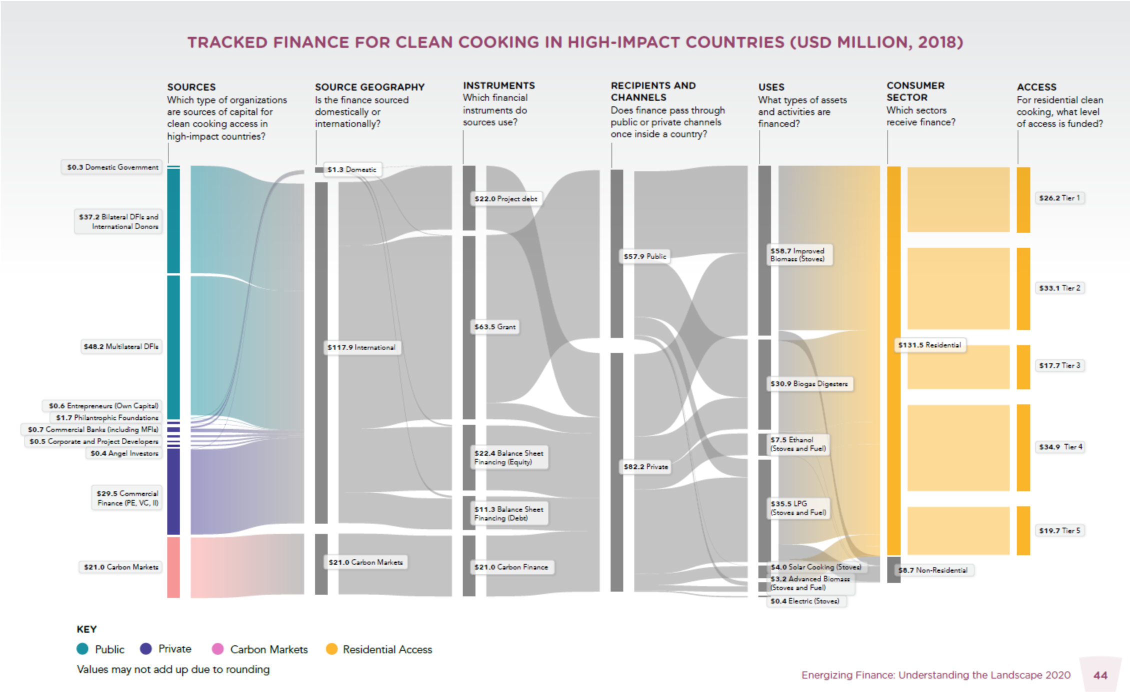

Figure 34. Finance for clean cooking in High-Impact Countries. Source: SEforAll, 2020.

Recommendation 24. To focus financing on Tier 4 and 5 cooking solutions in terms of energy efficiency and emissions, and to finance eCooking at the same level as other MECS technologies.

Development finance institution (DFI) financing: The World Bank Group launched the Clean Cooking Fund in 2019 with the goal of financing USD500 million over 5 years to catalyse USD2 billion in public and private investment (World Bank, 2019), the highest figure committed to date from a single institution for MECS transition. However, it is far from covering the funding needs estimated by the IEA, so the resources would have to be invested with a strategic logic, not only to catalyse other financing but to catalyse social transformation around cooking. An example of a strategic approach is followed by the MECS programme, launched in 2019 by UK Aid and provided with £39.8 million from UK Aid, which seeks to change the cooking paradigm by placing special emphasis on research, innovation, and discourse change.

Recommendation 25. To use international funding strategically to change the cooking paradigm.

National financing: Countries must have their own resources to finance the MECS-eCooking transition. The Energy Social Inclusion Fund (FISE) created in Peru to facilitate access to electricity, operational since 2012, may be a model to follow. The fund is financed by a surcharge on grid-connected electricity users, a surcharge on gas users, and a surcharge on hydrocarbon users (SEGIB et al., 2021).

Recommendation 26. To establish a national fund financed by surcharges on the most affluent users to promote MECS transition.

<u>Climate financing</u>

The Kyoto Treaty, which came into force in 2005, established an international carbon market and the Clean Development Mechanism (CDM) (UNFCCC, 2021) which allowed developing countries to generate certified emission reduction (CER) credits to sell to developed countries to meet their targets of reducing or limiting their emissions. CDM has been an important source of funding for ICS and LPG transition projects (Bailis et al., 2017). Following the adoption of the Paris Agreement in 2015, the instruments and conditions that will replace the CDM are still to be defined, and it is important that they permit MECS and eCooking programmes.

In parallel to the system established in the climate treaties, there is a Voluntary Carbon Market (VCM) that finances emission reduction projects with standards other than the CER. The World Bank has established the Carbon Initiative for Development (Ci-Dev) fund to mobilize more than USD250 million to acquire carbon credits under the Standardized Crediting Framework (SCF) (Ci-Dev, 2021). In addition, the Gold Standard Foundation has developed specific protocols for Cooking transition projects that promotes and is currently validating a methodology to measure the reduction of emissions of electric cooking appliances, which has been developed by Climate Care and the MECS programme (MECS, 2021b).

Recommendation 27. To permit the inclusion of MECS and eCooking programmes in the mechanism that will replace CDM.

Recommendation 28. To include eCooking programmes in climate programmes.

Private sector

Private investment in the ICS sector is low due to the perception of risk; however, this does not happen in the LPG sector, where large companies, both national and multinational, invest to develop the industry and the market. Therefore, the private financing of eCooking should follow a pattern more like that of the LPG than that of the ICS. On the other hand, the perception of risk can be reduced if eCooking programmes are integrated into broader energy policy or urban development programmes.

Another possible private financing option for eCooking is impact-investment, which in market-based approaches simultaneously seeks economic return and social impacts.

In order to stimulate private sector participation, the use of results-based financing (RBF) approach (Sida, 2015), which seeks to shift the objective of financing activities to results, is becoming increasingly common. This approach also allows us to precisely define and standardize the elements to achieve the results, while allowing companies to have the flexibility to organize (Development Bank of Rwanda et al., 2021). For example, ESMAP is using RBF to fund cooking transition in ten countries, with variations based on local conditions.

The World Bank claims that RBF is an effective instrument to incentivize private sector financing (ESMAP, 2020a); however, analysis of RBF programs in Nepal have shown that they have promoted the adoption of ICS but not its sustained use, because the programmes were focused on immediate results (Robinson et al., 2021).

Another possible private financing option for eCooking is impact-investment, which from market-based approaches simultaneously seeks economic return and social impacts.

The financing of the eCooking appliances sector is necessary in all phases of the value chain: manufacturers, distributors, retailers, electricity utilities, and consumers, with specific needs for each category of company.

Recommendation 29. To follow the LPG financing model more than the ICS one.

Recommendation 30. In results-based financing programmes, to seek permanent results rather than adoption results.

Recommendation 31. For the eCooking appliance sector to support all parts of the value chain.

4.2.5 Regulation

The electricity sector is highly regulated. To facilitate eCooking, the minimum electricity supply for a household should be MTF Tier 5 in power (at least 2 kW) and Tier 4 in energy (at least 3.2 kWh/day). In addition to eCooking, a high-power supply enables other uses, such as productive ones.

In some countries, such as Kenya, the regulation of electricity distribution companies prohibits them from selling products or services other than electricity. This is because a basic principle of regulation is not to mix activities that are regulated (natural monopolies, such as electricity distribution) with activities that are carried out in competition (retailing of electrical appliances). However, electricity distribution companies are in a good position to market or distribute efficient cooking equipment through on-bill financing mechanisms and/or subsidized programs, so it would be advisable to seek ways, without breaking the basic principles of regulation, to exploit this potential, e.g. by establishing cooperation agreements with the sector of companies distributing electric cooking equipment.

One of the problems of electric appliances in LMIC is their low quality, which results in a short life span and the need for a recurring expense for their replacement. It would be appropriate to establish minimum quality standards for eCooking equipment. Furthermore, given the differences in energy efficiency between models, it would be appropriate to regulate that manufacturers and distributors report on electricity consumption, both in absolute terms and relative to other products of the same category.

Regulating traditional fuels and stoves that are competitive with eCooking is complex. For example, in Kenya, attempts were made to regulate charcoal production from wood, but the measures have been ineffective and have had negative impacts on both the less well-off charcoal-using population and workers in the sector (Das et al., 2018). However, the regulation of minimum standards to be met by biomass stoves in China has led to a transformation of the domestic market.

Recommendation 32. To establish MTF Tier 5 in power (at least 2 kW) and Tier 4 in energy (at least 3.2 kWh/day) as the minimum standard for electricity service.

Recommendation 33. To seek ways for electricity distribution companies to promote eCooking, while respecting the basic principles of electricity regulation.

Recommendation 34. To establish minimum efficiency standards and efficiency labelling for eCooking appliances.

4.2.6 NGOs and Universities

The government sector and the business sector are the two key players in the cooking sector. However, there are hundreds of NGOs working to promote clean cooking, and although the scope of their projects is limited, they channel a significant part of the development finance institution (DFI) financing allocated to MECS.

NGOs have an important capacity to innovate and test new solutions, and some are leading the way in exploring the potential of eCooking (e.g., HIVOS, Tatetedo, Earth Spark). However, most continue to promote ICS that do not comply with the WHO AQG and do not offer eCooking appliances as an alternative or complement to ICS.

Universities and research centres have an important role in promoting eCooking due to the fact that many aspects of the deployment of eCooking among lower-income groups in LMICS are still unknown. For example, there is a need to know more about integrated electricity planning and MECS, standardized data and a need to promote geospatial tools (SE4All, 2020). Examples of research studies in recent years are those that are being funded through the MECS Challenge Fund (MECS, 2021a), whose results are open source.

A complementary research area to eCooking is that of HAP exposure, where it is important to advance in the development of systems for measuring pollutant concentrations that are simple and economical in order to generalize their use (Quinn, 2018). In the field of cooking and ventilation space, it is important to advance both in constructive solutions for kitchens and in the improvement of ventilation systems.

It is important to analyse the impacts of the cooking programmes that are developed, especially in the phase of permanent use, since in the literature there are multiple references to programs that do not reach the target population or whose objectives are not achieved, although initially the programmes were touted as successful.

Universities also have an important role in the training of people, both incorporating this theme in regular training and participating in capacity building.

NGO cooking transition programmes and university research both depend heavily on public funding, so administrations and international cooperation agencies have the capacity to influence their programmes. The work between NGOs and universities in cooking transition has yielded good results, complementing the capacity of the former to work in the field and research of the latter, and this must be promoted.

Recommendation 35. To promote NGO interventions to both comply with both the WHO AQG and provide eCooking appliances.

Recommendation 36. To involve universities in eCooking research and capacity building.

4.3 Industry structure and services

4.3.1 Physical infrastructure

A long distance between LPG and processed biomass distribution centres and customers is a barrier for adoption of these fuels, and an advantage for the promotion of eCooking. The use of electricity for cooking does not need a specific physical infrastructure but uses the one that already exists for other uses. In the case of households, the supply of electricity must be assured with or without eCooking, with a low increased cost because of eCooking. However, there is the drawback that eCooking adds an additional demand to these infrastructures. In the energy planning of a region, it would be useful to know the costs of strengthening electricity grids for cooking versus the development of gas infrastructure.

In general, substations, and transmission and distribution lines are designed to meet the growth in demand over the next 15-20 years, and in many cases still have room to support an increase in demand for eCooking (Leach, 2021). However, in other areas, the grids are already overloaded and the use of eCooking could exacerbate the problem. In most contexts, it is not known how much margin remains and better information regarding the capacity of the grid would provide better knowledge about the impacts of extending eCooking (SE4ALL, 2020).

For generation capacity, some countries have, or may have in the forthcoming years, surplus energy capacity (Power Africa, Web; NJIRAINI MUCHIRA, web). Ecuador has a surplus because of its high hydropower capacity and has tried to promote the use of induction stove since 2013, and the Kenya Power and Lighting Company promoted electric cooking for its customers in 2020 due to low demand during the Covid-19 crisis.

However, in many regions of the LMIC, blackouts and load shedding are common. In some countries, there is an evening peak caused by lighting and household demand, which must be addressed with more expensive generation technologies, increasing the average cost of kWh and/or causing load shedding. The time for preparing dinner coincides in part with the evening peak and could exacerbate this problem. In some parts of South Africa, where much of the population cooks with electricity, a program to promote LPG for cooking was developed precisely to reduce electricity demand in peak demand periods (Kimemia & Annegarn, 2016).

The kWh cost in microgrids is expensive, but still there may be potential for eCooking in microgrids. If the supply is through PV panels, the cost is much lower in shiny hours, and eCooking can be cost-competitive with alternatives (Bilich et al., 2021). The cost of electricity in isolated systems is even higher, but in special circumstances, for example, in refugee camps or linked to nutrition programmes where both food and the means to cook it are provided, the use of eCooking can be justified (WFP, 2020).

Recommendation 37. - To make comparative cost studies of infrastructure deployment of gas and electricity for cooking.

Recommendation 38. To study in each area the capacity of the generation, transport and distribution systems of the network for coping with an increase in demand for eCooking.

Recommendation 39. To establish electricity tariffs with hourly discrimination.

Recommendation 40. To promote eCooking where there is power surplus and in valley periods.

Recommendation 41. To promote efficient equipment that reduces electricity demand.

Sustainability of supply

In some contexts, there are difficulties in ensuring the supply of clean fuels due to problems in international markets or production in the local market, leading users to return to using biomass temporarily, or even permanently (Quinn, 2018).

Some countries face electric power supply deficits, either owing to structural power capacity or because of temporary scarcity due to climatologic or economic constraints. For example, in 2019, Zambia suffered an electricity supply shortage due to low water levels at hydropower dams related to a prolonged dry season caused by climate change. However, in most areas, supply failures that last for days are infrequent, and there is a tendency to strengthen grids and reduce SAIFI and SAIDI in many countries (World Bank, 2021a).

A study conducted in Ethiopia shows that frequent power outages do not discourage the use of eCooking when the cost of electricity is low (SE4all, 2020). To minimize the impact of short power outages, EPC can be used to maintain the temperature and pressure of the food until the electricity returns. In areas where the cost of electricity is very low and power cuts are very frequent, if the cost of batteries continues to fall, it could be cost-effective to use batteries for cooking with efficient appliances in the future, which would also result in higher levels of satisfaction with the other electricity services. Other clean technologies complementary to eCooking, such as LPG or alcohol stoves, can also be used as a backup.

Recommendation 42. To facilitate clean technologies complementary to eCooking in areas with frequent and/or long outages.

4.3.2 Markets

To match offer and demand, it is necessary to know the market, and conduct market research and customer segmentation (Fraym, 2021). The households most likely to use eCooking are those that are already paying a high price for cooking (Batchelor, Brown, Scott, & Sumanik-Leary, 2019; Putti et al., 2015).

To reach the most complex collectives, it is necessary to create new distribution channels, for example peer-to-peer women-led product distribution models (ESMAP, 2020a).

eCooking devices must include detailed information about their characteristics, usage, proper handling, forms of energy saving, guarantees, after-sales service, etc. Considering that some potential users may have a low educational level, perhaps even illiterate, it is important that the instructions for use and safety are produced in images and diagrams in order to facilitate understanding. Furthermore, to the extent that the equipment may have hidden defects or break down, there must be an after-sales service.

Recommendation 43. To conduct specific market research for eCooking and segmentation of customers.

Recommendation 44. To develop new distribution models for eCooking appliances.

Recommendation 45. To guarantee an efficient after-sales service.

Ongoing costs

Ongoing costs are the most relevant costs in cooking. In many cases, low-income households have no difficulty with small frequent payments; however, they do have problems with higher payments and costs, even if the total to be paid is the same or even less. For this reason, for those customers with the lowest income, one finds frequently products marketed in small quantities with a low total cost and a high unit cost.

One of the keys to the success of the deployment of mobile telephony among low-income households has been the possibility of using a prepaid system with small amounts. In the electricity sector, the use of smart counters and ICT allows the establishment Pay-As-You-Go (PAYG) models, where the user is paying according to consumption, in a relatively affordable way. The LPG sector addresses the problem of cash on hand with smaller cylinders that enable more frequent, smaller purchases, and with the implementation of PAYG (Shupler et al., 2021) systems.

Recommendation 46. To promote the Pay-As-You-Go model in electricity distribution sector to make it easier for low-income households to pay for eCooking.

Initial cost

A necessary condition for eCooking is the electric cooking appliances, although the availability of these is not a guarantee of their continued use. The demand of stoves and appliances is highly price sensitive (Pattananyak et al., 2019). In Sub-Saharan Africa, legacy or basic ICS cost only USD2–10, and intermediate ICS cost USD30–50, and the cost of a hot plate is in the range of USD10-30. Efficient eCooking appliances are more expensive, with the cost of a basic EPC being USD50-100 (ESMAP, 2020a). Most households in LMICS spend less than USD15 on their primary stove (ESMAP, 2020a), so the price of electric appliances is a barrier to eCooking.

Some measures to facilitate the acquisition of cooking appliances are:

- Subsidies to sellers and/or buyers based on the technology and income level of buyers (e.g., Rwanda Energy Access and Quality Improvement Project).

- Payment in instalments.
- On-bill financing from electricity distribution companies.
- Collective/bulk purchases to obtain a discount for quantity (e.g., the Global LEAP Awards Results-Based Financing programme, with the support of EnDev, are facilitating the sale of 5,000 EPCs in Kenya).
- To support supply chains.
- Free distribution, (e.g., to replace inefficient appliances, efficient equipment can be donated under certain conditions, as it has been done in some countries in the lighting sector to replace incandescent bulbs with LED).

In some cases, lending by financial institutions to enable the purchase of cooking appliances has also been tried, but many households are reluctant to borrow for reasons they do not consider essential. One form of getting greater acceptance is the creation of the revolving funds in women's saving groups.

Support for the purchase of cookware such as ferromagnetic pots for induction stoves or flat-bottomed pots for infra-red stoves must accompany the acquisition of eCooking appliances.

In areas where income is seasonal, for example, in rural areas that depend on agriculture, the promotion of eCooking equipment should be done at times when there is greater availability of income.

Recommendation 47. To facilitate the purchase of cooking appliances through subsidies, payment instalments, collective purchases, revolving funds, and other methods.

New products

To promote eCooking, a wide range of cooking appliances must be available. There are existing distribution channels for electrical equipment in all countries, unlike what happens with LPG or ICS, but these channels do not offer the most efficient cooking equipment.

There are opportunities to create new products for eCooking in LMICs. The production of efficient cooking appliances does not require complex technology, so in many countries they can be manufactured locally, adapted to the needs of the country. For example, in Kenya, the manufacturer Burn is developing an EPC to be produced locally, and is conducting a previous market study to adjust it to the potential demand (MECS, 2019).

Some small microgrids work with direct current (DC), but most of the electric cooking appliances work with alternating current (AC), which is converted to DC for the final energy consumption. There is potential to develop DC eCooking devices, in a similar way to the DC appliances for other services (radios, TV, fridges, etc.). For example, there are ongoing activities for development of DC induction stoves (Adhikari et al., 2018) and DC EPC (Larkins et al., 2021).

For isolated systems, some companies are beginning to develop systems where the focus is on eCooking and the rest of the electrical services are complementary (PESITHO, 2021). Another line of products is the development of eCooking systems with batteries in weak grids (Batchelor, 2018; Barton at al., 2020).

New products must be developed in a user-centred way. For example, the small size and portability of the equipment is a feature appreciated by many users as it allows cooking in many places (Pattanayak et al., 2019).

Recommendation 48. To promote local manufacturers of electrical cooking appliances.

Recommendation 49. To promote eCooking user-centered products and DC equipments.

4.4 User and community needs and perceptions

4.4.1 Affordability

Household income, or household expenditure, is a key determinant of MECS use: the lowest income households are most dependent on firewood and charcoal, while LPG and electricity are most prevalent among the highest income households. However, long-term and nationally-level subsidy programmes allow lower-income households to adopt MECS. Affordability does not depend exclusively on income/expenditure, but also on household cash flow, financing, or knowledge of incentives. The size and composition of the home can influence the adoption of MECS because larger households require more energy and spend more money in energy.

Income may be seasonal, fluctuating or sporadic. For example, households that make their living from agricultural production have more income at harvest time, and income depends on crop yields. When income decreases, it is common to increase free firewood gathering or purchase of the cheapest fuels. In the wake of the COVID-19 crisis and lockdowns, in countries such as Kenya, there was a reduction in revenue and an increase in the consumption of traditional fuels (ESMAP, 2021).

Recommendation 50. In major crises, such as COVID-19 or poor agricultural harvests, to establish specific measures for the subsidy of electricity for households with fewer resources.

4.4.2 Cost of energy alternatives

Access to cheap or free traditional fuels is one of the main barriers to transitioning to eCooking. Increasing the price of traditional fuels, through tax or regulations, in order to endorse eCooking is not recommended since low-income households have less money for other basic expenses. Furthermore, increasing it only for high-income households, which could afford it, can generate comparative grievances and social tensions.

However, in many places, the cost of charcoal and firewood is increasing steadily because of the higher demand and greater difficulty in production, and this will be one of the most important problems to address in the coming decades to ensure cooking affordability (ESMAP, 2020a). In many places, it is already cheaper to cook with electricity than with charcoal, and this situation may spread as the price of competitive fuels increases.

Many fuels have fluctuations in price. For example, the LPG price depends on the international market, and the price of firewood and charcoal can vary between the dry and rainy season due to its availability, and the difficulty of access to the collection and production areas. Although the cost of electricity also fluctuates, its variability is generally lower as the electric sector is highly regulated. Households that already pay for a fuel are more prone to shift to MECS, and when the price of LPG and charcoal rises, there is greater social awareness surrounding the cost of cooking. This is a good opportunity to introduce into the public debate the issue of the costs of cooking with different alternatives and eCooking.

Finally, many households are not aware of the non-economic cost of cooking with traditional fuels, especially in health, safety and time, and the inclusion of these costs may influence the choice of MECS among high-income households.

Recommendation 51. To conduct comparative studies and surveys on the cost of cooking with each alternative, for the whole menu and for the dishes in which eCooking is more advantageous.

Recommendation 52. To take advantage of times of rising charcoal and LPG prices to promote eCooking.

4.4.3 Perceptions and communication

<u>Perceptions</u>

Age and education influence the perception and adoption of MECS, especially when the systems are completely new and differ substantially from the old ones, which is the case of eCooking. The younger and more educated the women who cook are, the more likely it is that they will use eCooking. MECS are associated with modernity and convenience, and it is possible to use the aspirations of modernity and prestige to boost eCooking.

One of the main problems for eCooking adoption is that it is perceived as very expensive, when in some contexts it is not. It is important to campaign on the real cost of cooking with electricity, especially for some dishes and with efficient equipment. An example of such dissemination campaigns is the development of informative materials, such as "The Kenya eCook Book. How to save time and money" (Leary & Todd, 2019).

In terms of convenience, in some cases there is a perception that eCooking is not suitable for the preparation of all dishes. While it is true that some traditional dishes are difficult to prepare with eCooking, it is also true that the dishes that cannot be prepared with eCooking account for a very small percentage of the usual diets in most countries, and the suitability is not the most important factor for deciding on adoption (Ochieng et al., 2020). In any case, cooking programmes should include at least two appliances that can be used simultaneously in order to expand cooking options.

Some ICS only work well properly under certain conditions (size of firewood, closed combustion chamber, regular maintenance, chimney cleaning, etc.). eCooking appliances need no special requirements for running, although in some cases, there may be a perception that it is not safe, especially if cooking under high pressure. Most eCooking appliances are easy to use in an intuitive way, although the operation of the EPC and microwave ovens may be an exception and may require some training.

Another advantage of eCooking is that it allows the possibility of cooking more frequently. For example, 45% of people who participated in an eCooking programme in Haiti reported that they had increased the frequency with which they cooked (Bilich et al., 2020).

Recommendation 53. To associate eCooking with women's aspirations of modernity and prestige.

Recommendation 54. To raise awareness that eCooking and efficient appliances permit the preparation of most meals with a similar taste to traditional stoves, being safe and offering at least two technologies to operate simultaneously.

Recommendation 55. To make materials/campaigns about the real cost of eCooking.

Behaviour change communication

In addition to schemes to promote cooking systems through rewards schemes, Matin & Roe (2016) have highlighted the need for shaping knowledge through demonstrations, peer to peer communication, social networks, or influential people. Furthermore, they point out the importance of social support to increase cultural acceptance through visits by health teams, community sales agents or community leaders.

Marchand (2021) has also highlighted the importance of using existing networks, infrastructures and knowledge to promote. Reaching younger women requires using their language and channels, especially social media.

Recommendation 56. To use behavioural change communication strategies to increase the initial interest and uptake of eCooking.

4.4.4 Gender approach

Women must be at the center of any eCooking transition intervention. They are the ones who mostly cook and know the needs to be covered. But also, in many cases, they are the key players in spreading new ways of cooking and can participate in transition programs in communication and marketing.

There are differences between female- and male-headed households in terms of affordability and willingness to pay. In many cases, men and women have different decision power in the households (DBR, 2021). The introduction of induction stoves in Nepal seems to be changing some gender norms, causing men to cook more and prepare, for example, tea or snacks (Marchand, 2021). Cooking transition programs can serve either to empower women and reduce inequities, or to consolidate existing gender structures.

Recommendation 57. To use eCooking transition programs to empower women and reduce gender inequities.

4.5 Conclusion. Long-term strategy.

Table 22 lists the measures described above.

Table 22. Main measures to promote eCooking. Source: own elaboration.

Influencing policy
1. To spread the narrative that, in the context of climate change and the movement towards a carbon neutral economy, eCooking is an inevitable option, and stacking is a fundamental part of the transition process.
2. To contrast the arguments against eCooking with the arguments for modernization aspiration, demographics, economics, and electrification.
3. To establish an alliance to promote eCooking and assist LMIC to plan, finance and implement eCooking transition on a national scale.
4. To raise awareness among professionals in the electricity sector and energy planners about eCooking opportunities.
Policies
5. To review the international discourse on eCooking and include it as a basic electricity service.
6. To establish at national level a commitment to reach MTF's Tier 4 and 5 with a specific mention to eCooking.
7. To use the COVID-19 recovery plans to impulse eCooking.
8. To include the eCooking demand when planning the electricity scenarios.
9. In surveys on cooking systems, to measure the utilization of all cooking systems and the conditions of the cooking space.
10 . In national emissions inventories, future emissions scenarios and NDCs, to break down emissions from cooking by fuels and electricity, specifying CO2eq emissions and short-lived pollutants.
11. To make and publish LCA for different combinations of fuel-stove or electricity-appliances for cooking.
12. To establish plans to diminish charcoal consumption.
13. To accurately calculate the HAP-attributable health burden impacts.
14. To raise public awareness of the health risks of HAP, their associated costs, and how to avoid exposure.
15. To establish the political and operational direction of MECS transition in the Ministry of Energy.
16. To do pre-feasibility studies of eCooking in the cooking transition programmes, and give several technological options, including eCooking appliances.
17. To foment communication between all the stakeholders involved in cooking programmes.
Subsidies
18. Governments must understand that subsidies are essential to fill the gap between the cost of MECS and the capacity to pay of low-income households, and subsidies should be targeted to these households.
19. To establish a lifeline tariff with the lowest possible price for low-income households to supply non-cooking and cooking services.
20. To establish a very low or free electricity connection fee for low-income households.
21. To avoid establishing high subsidies to LPG.
22. To shift subsidies from LPG to electricity, specially to promote access to electricity, eCooking and renewable energy.
23. To reduce import tariffs for the most efficient cooking equipment.
Financing
24. To focus financing on Tier 4 and 5 cooking solutions in terms of energy efficiency and emissions, and to finance eCooking at the same level as other MECS technologies.
25. To use international funding strategically to change the cooking paradigm.
26. To establish a national fund financed by surcharges on the most affluent users to promote MECS transition.
27. To permit the inclusion of MECS and eCooking programmes in the mechanism that will replace CDM.

28. To include eCooking programmes in climate programmes.
29. To follow the LPG financing model more than the ICS one.
30. In results-based financing programmes, to seek permanent results rather than adoption results.
31. For the eCooking appliance sector to support all parts of the value chain.

Regulation

32. To establish MTF Tier 5 in power (at least 2 kW) and Tier 4 in energy (at least 3.2 kWh/day) as the minimum standard for electricity service.
33. To seek ways for electricity distribution companies to promote eCooking, while respecting the basic principles of electricity regulation.
34. To establish minimum efficiency standards and efficiency labelling for eCooking appliances.

NGOs and Universities

35. To promote NGO interventions to both comply with both the WHO AQG and provide eCooking appliances.
36. To involve universities in eCooking research and capacity building.

Physical infrastructure

37. To make comparative cost studies of infrastructure deployment of gas and electricity for cooking.
38. To study in each area the capacity of the generation, transport and distribution systems of the network for coping with an increase in demand for eCooking.
39. To establish electricity tariffs with hourly discrimination.
40. To promote eCooking where there is power surplus and in valley periods.
41. To promote efficient equipment that reduces electricity demand.
42. To facilitate clean technologies complementary to eCooking in areas with frequent and/or long outages.

Markets

43. To conduct specific market research for eCooking and segmentation of customers.
44. To develop new distribution models for eCooking appliances.
45. To guarantee an efficient after-sales service.
46. To promote the Pay-As-You-Go model in electricity distribution sector to make it easier for low-income households to pay for eCooking.
47. To facilitate the purchase of cooking appliances through subsidies, payment instalments, collective purchases, revolving funds, and other methods.
48. To promote local manufacturers of electrical cooking appliances.
49. To promote eCooking user-centered products and DC equipments.

Affordability

50. In major crises, such as COVID-19 or poor agricultural harvests, to establish specific measures for the subsidy of electricity for households with fewer resources.

Cost of energy alternatives

51. To conduct comparative studies and surveys on the cost of cooking with each alternative, for the whole menu and for the dishes in which eCooking is more advantageous.
52. To take advantage of times of rising charcoal and LPG prices to promote eCooking.

Perceptions and communication

53. To associate eCooking with women's aspirations of modernity and prestige.
54. To raise awareness that eCooking and efficient appliances permit the preparation of most meals with a similar taste to traditional stoves, being safe and offering at least two technologies to operate simultaneously.
55. To make materials/campaigns about the real cost of eCooking.
56. To use behavioural change communication strategies to increase the initial interest and uptake of eCooking.

Gender approach

57. To use eCooking transition programs to empower women and reduce gender inequities.

Some of these measures can be combined into a few broader lines of action that could form a long-term strategy:

- **Gradual implementation of eCooking:** The transition to eCooking needs to be gradual to allow time for strengthening the capacity of the electricity system and user adoption, and it needs to be linked to each country's energy and electricity planning.
- **Coexistence of eCooking with other cooking technologies:** During a long period, eCooking will coexist with biomass and LPG stoves in a clean stacking process. The use of several technologies will allow efficient cooking task allocation, adaptation to the style of each cook, and resilience to the fluctuations in income or the prices of energy sources.
- **Biomass stoves still need to be considered**: When eCooking stacks with biomass stoves, measures to minimise the exposure of the population to HAP must be promoted.
- **Lifeline electric tariff**: Establishing an affordable lifeline tariff is the best way to promote both access to electricity and eCooking. States and Governments must assume their responsibilities and obligations to promote energy access for all and subsidize people that cannot afford it.
- **Interventions at national level:** The problem of HAP and the need for transition to MECS affect a large part of the population in LMIC, so there should be a nationwide programme of both awareness campaigns and policies to facilitate access. However, this does not mean that there are no programmes targeted at groups with specific characteristics (e.g., young women, population in areas with huge deforestation, charcoal buyers, very low-income households, etc.)
- **Awareness raising in the electricity sector:** Individuals and institutions working in the electricity sector can make a substantial contribution to a rapid eCooking transition, so it will be cost-effective to raise their awareness about the potential and needs of eCooking**.**

5. CONCLUSIONS AND FURTHER RESEARCH

At the end of chapters 2, 3 and 4, the main conclusions and future lines of research related to the topics covered in these chapters have been set out in detail. In the following sections, these are synthesised and related to provide an overview.

5.1 Conclusions

This thesis has examined the potential of eCooking as a means of making progress towards the achievement of SD 7, since the pace of progress has been insufficient so far, and radical change in the coming years is imperative. The number of people without access to affordable, reliable and modern energy cooking services (MECS) was around 4 billion in 2019, more than half of the world's population. Progress on access to MECS is very slow and the number of people without access to clean cooking has only been reduced by 13% in the last decade. Given the current policies and commitments, the number of people without clean cooking facilities will be reduced by less than 10% by 2030.

Cooking with electricity (eCooking) has advanced in Low- and Middle- Income Countries (LMIC) from being 3% of the total cooking in 2000 (140 million) to 7% in 2019 (450 million), but it is still far from realising its potential and nearing the figures of developed countries, such as Spain, where it is used in 70% of households.

Historically, eCooking has only been considered suitable for affluent countries or healthy urban households. However, the international perception of the potential of eCooking to address the cooking problem has changed rapidly during the last two years, and there is an international political call for 40% of households to use eCooking with 60% of the electricity supplied from low-carbon sources by 2030. Beyond political decisions, concrete measures need to be developed to accelerate its implementation.

Fuel stacking, the use of several energy sources and appliances, is the normal way of cooking transition into MECS. As biomass, LPG and electricity will coexist in households for many years to come, it is necessary to have a thorough understanding of these technologies to promote their optimal combination in terms of social, environmental and economic impacts.

Personal exposure to high concentrations of cooking pollutants is the main reason for the health impacts of cookstoves, and their reduction should be an objective of all cooking transition programmes. Exposure depends not only on the fuel-stove combination but also on space, ventilation, and personal practices, so these variables must also be considered.

The main methodologies for measuring the impacts of cooking on health, gender equality, the environment, climate change and the economy have been described in this work. The impacts are highly contextual and depend on many boundary variables; therefore, extrapolating data from one context to other risks generating high levels of error. In many cases, fieldwork is required to obtain reliable data, which makes measuring impacts difficult and expensive.

To lay the foundations to assist decision-making for the integration of electric cooking and MECS in the electrification planning of unserved areas, a methodology has been developed, a set of reference values for the main variables has been selected, and the methodology and values have been tested in Nyagatare District in Rwanda. Simulations have been carried out using the Reference Electrification Model (REM), which operates with a high spatial resolution, calculating detailed network designs for microgrids and grid extensions whose layouts go down to the end-buildings. REM allowed to find the least cost combination of grid extensions, microgrids and isolated systems, as well as the costs of each system.

The methodology considers three electrification scenarios: the “Basic Scenario”, where electricity supplies basic services; the “Complete Scenario”, where in addition to covering basic services, the entire daily cooking load is carried out with electricity; and the “Stacking Scenario”, where in addition to covering basic services, half the daily cooking load is carried out using energy efficient electric appliances and the rest with other cookstoves.

In the Nyagatare District case study, the hypothetical penetration of electric cooking would substantially change the fraction of households electrified with each electrification mode in the least cost plan and would lead to a reduction in the per unit kWh cost, both for households and for all consumers.

Under the adopted assumptions and input data, our results show that electric cooking can be cost-competitive compared to LPG for grid-connected households, although not for non-grid-connected households. Its competitiveness with charcoal will depend on the future cost of this fuel in rural areas. Replacing firewood and charcoal with electricity for cooking is an effective means of achieving GHG emission reductions.

Clean stacking with electricity significantly reduces the per unit cost of the kWh and the need for collection of non-renewable biomass, with a limited increase in global cost for electrification and cooking. Therefore, this scenario is a transitional option for meeting MECS.

Some aspects of the model still need to be improved – some estimations of input data made due to lack of information need to be replaced by more accurate ones, while caution should be exercised when extending results from one geographical area to another. Nonetheless, the results obtained do indicate that the methodology developed provides useful information to assist decision-makers in planning universal energy access.

Fifty-seven measures have been identified to promote e-cooking to enable the context, to support the industry structure and services, and to meet user and community needs.

It is important to disseminate the narrative that, in the context of climate change and the movement towards a carbon neutral economy, eCooking is a necessary option, and stacking is a fundamental part of the transition process. The international discourse must change to include eCooking as a basic electric service, and climate mitigation and adaptation plans must be used to boost eCooking. The establishment of a lifeline tariff with the lowest possible price for low-income households, thus facilitating both electricity access and eCooking transition, is the best option.

On the infrastructure side, it is necessary to study in each geographical area the capacity of the generation, transport, and distribution systems of the power sector for coping with an increase in demand for eCooking. Regarding markets, it is advisable to conduct specific market research for eCooking and segmentation of customers, to inform the actual cost of cooking with each technology, to associate eCooking with women's aspirations of modernity and prestige, and to promote the Pay-As-You-Go model in the electricity distribution sector to make eCooking payment easier for low-income households. eCooking transition programs must be used to empower women and reduce gender inequalities.

Individuals and institutions working in the electricity sector can make a substantial contribution to achieving access to MECS through eCooking. For this reason, it is worthy to raise their awareness about the potential and needs of this technology.

5.2 Further research

Cooking impacts vary widely from household to household and among contexts. At present, there is no typology of household profiles, cookstoves, and cooking modes that reliably relates typologies to impacts. Having such typologies would allow the estimation of impacts through rapid surveys, which would be an important step forward.

To improve cooking and electrification integrated planning, it is necessary to complement the Reference Electrification Model (REM) with a model for the technologies that compete with electricity. The associated demand also needs further development.

On the cooking fuel supply side, a georeferenced layer with LPG, charcoal, and firewood distribution networks must be developed in addition to the estimation of the fuel costs at the household level, the hotspots of deforestation and charcoal production, the availability and cost of stoves and electric cooking equipment, government policy priorities, public subsidy options, and the plans of businesses and the civil society.

On the demand side, additional information should be gathered for each household: cultural preferences, electricity and fuel~~s~~ demand profile, prioritized technologies for stacking, their ability and willingness to pay, household expenditure, health impacts, and time available for collecting free firewood.

More accurate results require more precise input data. Fieldwork would be needed to establish household profiles that are representative of reality, including energy and time consumption for cooking, indoor air pollution, costs incurred and the role of men and women.

In this study, it was considered that the generation capacity of the grid could reliably meet the demand, including peak hours. However, this may not be the case if demand growth is faster than supply growth. Our estimations of greenhouse gas emissions have not considered the life cycle of fuels and electricity due to lack of information, so they are underestimated.

The measures identified to promote electric cooking are of a general nature. In order to reach a more precise understanding of this topic, several national case studies designed to measure their feasibility, impact and cost-benefit need to be carried out.

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