

VOICE OF FUTURE GENERATIONS



BEYOND FIRE:
HOW TO ACHIEVE
SUSTAINABLE COOKING

IMPRINTS

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“ For too long, cooking has been a silent killer in developing countries around the world. Finally we are seeing momentum around this issue.”

Kofi Annan¹

1 See: http://cleancookstoves.org/resources/reports/fiveyears.html?utm_campaign=homehero

FOREWORD

Across the world, 3 billion people rely on traditional biomass fuels, such as firewood, charcoal or animal dung to meet their energy needs for cooking, causing serious adverse consequences for the environment, health, and economic development of the population.

Reliance on wood and charcoal for cooking has a number of well-recorded negative effects, including deforestation, soil erosion or loss of biodiversity. Exposure to household air pollution from cooking with solid fuels causes 4.3 million premature death according the World Health Organisation. Moreover, such inefficient cooking fuels and technologies are particularly affecting women and children, who work an estimated 8-9 hours per week in collecting and transporting cooking fuels, and will be most exposed to the toxic fumes. This clearly impacts on their health, limits opportunities to improve their education, and represents a massive opportunity cost in regions of the world with tremendous potential for future economic development and poverty reduction.

In many countries, cooking-related energy use account for over 90% of household energy consumption, as highlighted by the International Energy Agency. Yet, up to the present, much of the debate and solutions revolve around the generation of electricity.

While we witness the global uptake and enormous cost reduction of renewable electricity, it would be a mistake not to embark the cooking sector on this journey. Otherwise, there is a real risk of leaving untouched much of the energy supply mix, as well the challenges it entails. The shift to a new thinking will thus be critical to ensure universal access to affordable, reliable and sustainable energy for all the needs. This report provides some highly valuable insights on the current cooking practices and suggests a new integrated mindset on sustainable cooking - one 'beyond fire'.

So far, the majority of governments and international donors seeking to step up their involvement in addressing the problem have focused their efforts towards improved cook stove technologies. These technologies can certainly play a crucial role in addressing the challenge of sustainable cooking. However, they are, at best, an interim solution. The harvesting of wood and production of charcoal continue to have significant negative impacts on the environment and on human health. The sheer power of demographics will require huge amounts that are incompatible with more sustainable production options –only in Sub-Saharan Africa the population is projected to almost triple by 2060, reaching 2.7 billion. And, when the time of many women keeps being largely consumed by gathering wood or charcoal, countries are holding back a valuable labor force who could be engaging in more productive activities.

Failing to fundamentally change the energy mix in the cooking sector is clearly not an option. We need a breakthrough transition towards truly long-term, sustainable solutions which do not leave anyone behind. To inform and push the discussion beyond wood and charcoal-based solutions, this broad analysis on sustainable cooking suggests how the various renewable energy technologies could help accelerate this transition. The goal of this report is not to prove that a particular pathway will ever fully or exclusively replace the use of traditional biomass for cooking purposes: rather, the goal of the report is to critically evaluate the various different technological pathways and the barriers along the way.

Predictably, financial constraints has been widely cited as the key obstacle to the uptake of new sustainable technological solutions. Even though this is undoubtedly of major importance, even more for people in poor remote areas, embracing sustainable renewable energy cooking appears to be within closer reach than ever before. The cost of renewable energy and storage technologies keeps decreasing at a rapid pace. And, as fossil fuels no longer offer strong returns, traditional investors such as sovereign wealth funds and pension funds are starting to bet on renewable energy solutions. Therefore, notwithstanding the challenges, there is room for optimism. And as the renewable energy landscape transformation shows us, when governments decide to move forward, they can move forward.

To succeed, this report aims to become a tool for policymakers to understand what is at stake and suggest concrete steps to drive this transition towards universal sustainable cooking. With the right legal framework, concerted policy attention and public support, achieving universal cooking can become a reality and we will be able, finally, to go beyond fire.

This report represents a collaborative effort involving four organizations, and a wide range of stakeholders who provided hugely valuable comments and critical advice for improving our work. Whereas the overview reflects the combined judgement and scrutiny of the authors, it goes without saying that the views and recommendations presented in the report do not necessarily reflect the exact opinions from all single reviewers.



Eco Matser



Stefan Schurig

EXECUTIVE SUMMARY

Achieving sustainable cooking is one of the great challenges of our time. An estimated 4.3 million premature deaths are caused each year by indoor air pollution due to cooking practices still widespread in many parts of Southeast Asia, Latin America, and Africa (WHO 2016). The difficulty of finding cost-effective substitutes for traditional cooking fuels, most notably wood and charcoal, and of fostering their adoption among communities whose citizens have limited incomes and have rarely if ever known anything else, poses a formidable challenge.

Citizens in rural areas, frequently women and young children, work an estimated 8-9 hours per week in collecting and transporting cooking fuels (World Bank 2006); this represents a massive opportunity cost in regions of the world with tremendous potential for future economic development and poverty reduction. In addition, the unsustainable harvesting of fuel wood is accelerating the rate of deforestation in many parts of the world, contributing to a host of related challenges including soil erosion, loss of biodiversity, desertification, and even the reduced availability of potable water (Sanga and Jannuzzi 2005; Hilderman 2010; UNESCO 2012). When added to the high human cost of indoor air pollution, **these complex and often interrelated problems underscore the need for new solutions and new thinking around the question of cooking.**

Over the past three decades, the majority of the focus in the cooking sector in Southeast Asia and Sub-Saharan Africa has been on promoting improved cook stove technologies rather than on a fundamental transition of the underlying energy sources or fuels being used;² this can be seen in the many of the national energy strategies recently developed, notably in sub-Saharan Africa (AfDB 2015; GACC 2016; ECREEE 2014). While the promotion of more efficient cook stoves remains an important interim solution and has delivered impressive results in certain countries, **this report argues that focusing on improved cook stoves is neither a truly long-term nor a truly sustainable solution to the challenge of cooking.**

Much of the biomass for use in cook stoves (whether efficient or not) is not sustainably harvested; moreover, it is often not “renewable” in the traditional sense due to unsustainable rates of deforestation, soil loss, and desertification. And while efficient cook stoves may significantly mitigate many

of the critical environmental issues related to cooking, they continue to contribute to a host of other social and economic problems, including gender inequality, low child literacy rates, as well as low labor market participation rates, all of which hinder economic diversification, entrench social injustices, and undermine long-term economic prosperity. Furthermore, and perhaps most critically, continued reliance on wood-based fuels as the primary cooking fuel is unsustainable in the medium to long-term simply due to demographics: the population of the population of Sub-Saharan Africa (SSA) alone is projected to almost triple by 2060, reaching as high as 2.7 billion, up from 1 billion in 2015 (World Bank 2015). At such a high rate of population growth, continuing to rely primarily on wood-based products (whether firewood, pellets, charcoal, or others) will become less and less sustainable, regardless of how efficiently the biomass is harvested, produced, or consumed.

In light of these various interrelated challenges, this report aims to critically evaluate the viability and scalability of existing alternatives, with a focus on four (4) potential (and non mutually exclusive) pathways:

1. The use of **solar home systems** (SHS) to power electric cooking appliances;
2. **Renewably-powered mini-grids** to power electric cooking appliances;
3. **Distributed biogas systems** powered by agricultural and other wastes;
4. Renewably-generated **power to gas** (P2G) for use with conventional gas stoves.

The goal of the report is not to prove that a particular pathway will ever fully or exclusively replace the use of traditional biomass for cooking purposes: rather, the goal of the report is to critically evaluate the various pros and cons, compare the current costs of different technological pathways, and highlight the different challenges that each faces. Ultimately, it is likely that a variety of different cooking technologies will continue to co-exist and compete with one another well into the 21st Century, not least because cooking is so deeply rooted within local customs, traditions, history, and culture, but also because the adoption of new technologies rarely if ever fully displaces previous technologies (IEA, 2006; World Bank 2014; Sovacool 2016). Just as most industrialized nations continue to use wood or charcoal occasionally in addition to using electric or gas-based cooking, different energy sources and fuels typically co-exist with one another even as nations develop: in the cooking sector this phenomenon has been referred to as “fuel stacking” (IEA, 2006).

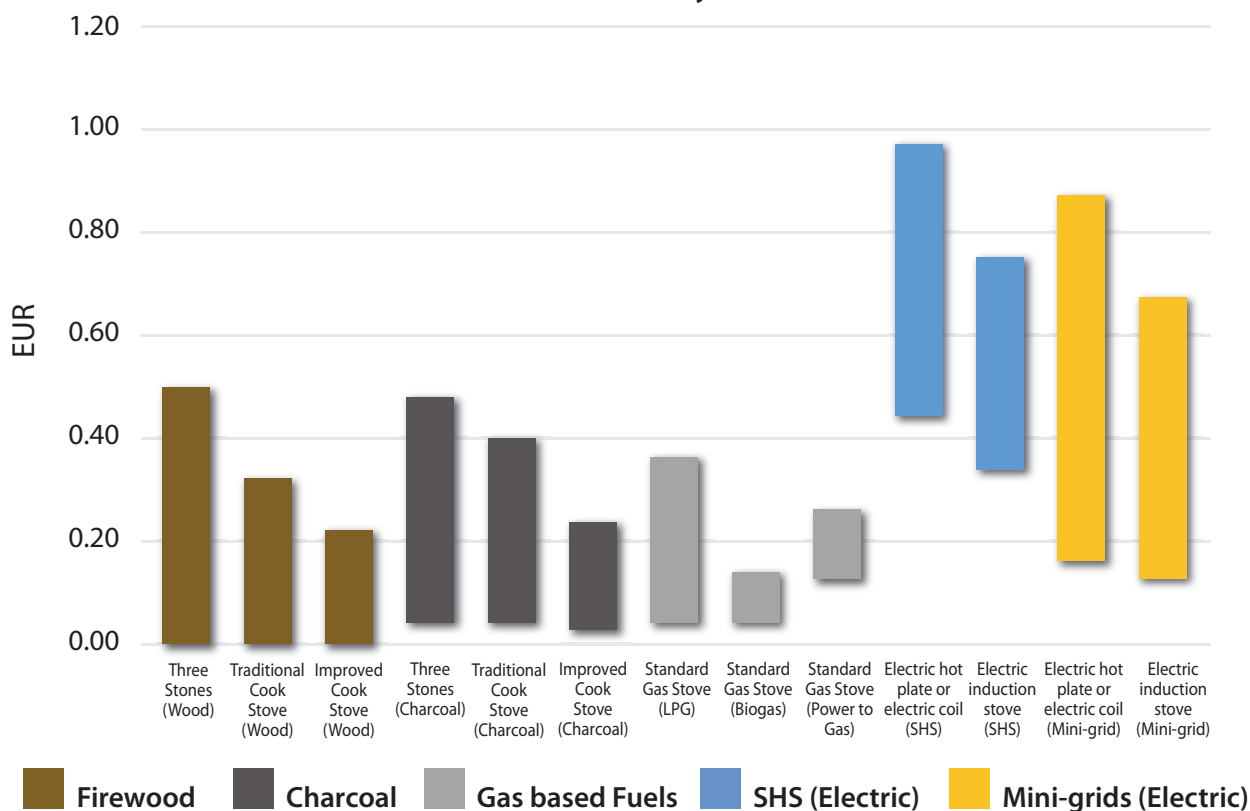
² The authors recognize that considerable efforts have been made to promote the use of liquefied petroleum gas (LPG) in certain jurisdictions as well. For the purposes of this report, however, LPG is not considered a long-term sustainable solution (see Section 1 below).

Moreover, overcoming the economic cost barrier is only part of the challenge: **sustainable cooking technologies must be well adapted to individual communities' way of life**, and must be able to be easily integrated with prevailing cooking habits (Goodwin et al. 2014). This means that the transition to other fuel types, whether electricity or otherwise, is likely to be a gradual process, underscoring the need to increase efforts to accelerate this transition now.

In defining what is meant by “sustainable cooking”, this report adopts the three pillars of sustainability. According to this definition, a technology has to be **environmentally, socially**, as well as **economically** sustainable to be considered truly sustainable in the long-term. This provides one of the foundational elements of the report.

In order to provide a comprehensive comparison of existing cooking options and of alternative cooking pathways, this report has calculated the costs of producing a unit of thermal energy (in GJ) via each of the main cooking options under consideration. This benchmarking is considered necessary in order to objectively compare the different costs of different cooking pathways. At the core of this calculation is that **the estimated useful energy needed for cooking per person is 1GJ per year**, based on Sanga and Januzzi 2005, and supported more recently by Demierre et al. 2014. Drawing on this number, the figure below provides a summary of current cost ranges, in EUR/GJ, of the various cooking options considered within the report. Note that costs vary largely within each technology category due to the wide range of cost factors, including total system costs, appliance efficiency, user behavior, etc. Also, the calculation (for instance in the case of electric options) is based on accepted ranges of costs based on the approximate levelised cost of energy, or LCOE, of different options, rather than a component-based approach that gathers and analyses the costs of each individual cost factor (e.g. panels, wiring, etc.) The exception to this is the calculation for biogas digesters, where it was necessary to conduct a more detailed financial modeling. The assumptions used are outlined in greater detail in Section 5.

**Cost Ranges of Various Cooking Technologies
(Per Person, Per Day, in EUR)**



While electric-based cooking options remain more expensive than the other options examined, this is likely to change as the costs of renewable energy technologies continue to decline and as further economies of scale are reached. In addition, it is important to note that the technology cost ranges included above do not reflect the social, economic, health, and environmental externalities; internalizing these externalities would significantly improve the relative economics of the electric cooking options. In addition, electrification supports a multiplicity of other development objectives, including improved safety and security, better educational achievement, improved sanitation?, gender equity?, while also increasing residents' economic opportunities. These and a range of other factors make the co-benefits of electric pathways arguably far larger than for the P2G pathway, for instance. Biogas, however, also brings its own co-benefits besides health and reduced CO2 emissions: the slurry from biogas is a very valuable fertilizer and can help increase crop yields while reducing the need to purchase chemical fertilizers. As a result, the slurry produced can significantly boost farmers' incomes and improve their overall economic situation. These various co-benefits should be borne in mind throughout the report.

Another key factor, however, is that electric pathways have been shown, in practice, to be less effective at actually *displacing* firewood and charcoal use than biogas and other similar systems (World Bank 2014). Field research has shown that introducing electric cooking only reduces the consumption of firewood and/or charcoal between 10% and 40%. In contrast, **the displacement rate for households equipped with biogas systems has been shown to be significantly higher, ranging between 66% to as high as 80%**. Put differently, based on current social, behavioral and cost dynamics, biogas systems have proved to be significantly more effective at actually reducing reliance on firewood, charcoal and other traditional fuels (World Bank 2014). Whether this will improve over time as residents gradually become more familiar with electric cooking, leading to a gradually increasing displacement rate, remains to be seen.

The question becomes whether it is more cost-effective to provide electricity in smaller-scale systems (either SHS or mini-grids) to meet basic electricity needs, while meeting cooking needs with alternative (and currently more affordable) non-electric pathways such as P2G, LPG, or distributed biogas systems.

Beyond Fire: 5 Steps to Achieve Sustainable Cooking

The following list outlines five key steps to help accelerate the transition to sustainable cooking:

- 1. Governments need to set clear goals to transition away from firewood and charcoal.** The current energy strategies being developed throughout most of Africa and Asia are not doing enough to drive a meaningful transition toward sustainable cooking solutions. Current strategies largely focus on improved cook stoves and the build-out of LPG infrastructure, failing to recognize the tremendous potential of alternative cooking solutions such as renewable electricity, biogas, and P2G. By focusing largely on improved cook stoves, many in the international community are choosing to ignore the underlying demographic trends that are likely to make any long-term reliance on wood-based fuels for cooking unsustainable in the long-run. In order to make meaningful progress toward sustainable cooking, governments will need to commit to far more ambitious goals, including clear strategies and clear financing mechanisms to implement them, and donor organizations will need to think beyond the current focus on improved cook stoves.
- 2. Governments should undertake root-and-branch reform of fossil fuel subsidies, which often benefit middle and upper-income residents, and re-allocate them to support a rapid scale-up in sustainable cooking technologies.** In contrast to existing fossil fuel subsidies around the world, which tend primarily to benefit citizens with medium to high income levels, targeted support for sustainable cooking technologies tend, by default, to support lower income households. Re-allocating fossil fuel subsidies to accelerate the transition toward sustainable cooking would bring massive and lasting benefits to sustainable development, and would contribute significantly to re-balancing the major inequities that continue to persist between urban and rural regions. Reforming fossil fuel subsidies and re-allocating the proceeds to support sustainable cooking is perhaps one of the single most impactful steps that governments around the world can take to accelerate the transition.

3. Governments and donors around the world need to fund a greater range of projects to demonstrate the viability of sustainable cooking solutions, including electric, biogas, and P2G pathways, as well as to support the scale-up of new business models in the cooking sector.

These kinds of projects can be extremely valuable in order to gather cost and performance data, analyze behavioral and other challenges, while driving further technological innovation and cost reduction. Moreover, strategically supporting the emergence of new business models can help give rise to replicable, scalable projects at various points of the cooking value-chain. Skepticism of alternative cooking solutions remains high, not least among end-users: one of the best ways to overcome this is first to demonstrate their viability, and then to help drive technological improvement and cost reduction by expanding the market, and improving the overall mechanisms of delivery.

4. Governments, in partnership with international donors, should introduce clear policies and incentives to reduce upfront costs. This can involve targeted grants to encourage adoption and foster economies of scale; it can also involve other policies to help bridge the cost gap, such as “feebates” (e.g. additional fees on certain items such as air

conditioning units or automobiles that are allocated to support rebates on other technologies, in this case, sustainable cooking technologies); a further approach might involve the targeted use of tax or duty exemptions, such as those frequently offered on solar PV components. These measures may be combined with other legal and regulatory measures, such as restrictions on charcoal use and distribution, or better monitoring and delivery mechanisms to ensure that the benefits reach end-users.

5. International climate finance should be mobilized to play a far greater and more direct role in supporting the transition to sustainable cooking, including through the wider use of climate bonds. *Scaling up sustainable cooking represents one of the most significant opportunities worldwide to generate major climate change mitigation and adaptation “win-wins”: reducing reliance on traditional fuels such as firewood and charcoal, improving human health, while helping to preserve forest ecosystems, ecological resilience, and local biodiversity.* New financing mechanisms such as climate bonds could significantly expand the volume of capital flowing to the sector, and yield wide-ranging benefits for both local citizens and the global climate



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INTRODUCTION:

An estimated 2.8 billion people around the world cook with either wood, dung, coal, or charcoal to feed themselves or their families, placing tremendous strain on the surrounding environment and on human health, while holding back many regions' economic development (Goodwin et al. 2014).

- As of 2015, an estimated 741 million people in sub-Saharan Africa alone rely on traditional biomass as their primary cooking fuel, a figure that is projected to rise to 918 million by 2030 as population growth continues (GEF 2013). This is likely to put significant additional strain on already stressed forest resources in many parts of the continent. According to a major report published a few years ago by the United Nations Environment Programme, Africa is experiencing a rate of deforestation twice the global average (UNEP 2008).
- In several countries in sub-Saharan Africa, the use of wood and charcoal represents over 90% of total final energy consumption (FAO 2015).
- Unsustainable firewood and charcoal use is the single largest source of greenhouse gas emissions (GHGs) in many countries and significantly exacerbates the negative effects of global climate change (World Bank 2014). Burning firewood and charcoal accelerates deforestation and soil loss, while increasing a region's exposure to a host of other environmental risks such as desertification, loss of biodiversity, and water scarcity.
- Reliance on such traditional fuels for cooking was a direct cause of an estimated 4.3 million pre-mature deaths around the world, mostly of women and children, due to high levels of indoor air pollution (WHO, 2016)
- There is an estimated USD \$123 billion in annual costs to human health, to the environment, and to local economies caused by the use of solid fuels like wood and charcoal for cooking (GACC 2016).

Transitioning to more sustainable forms of cooking in regions like sub-Saharan Africa therefore remains a pressing global issue. As these few facts highlight, finding sustainable alternatives to cooking is not only an environmental imperative; it is critical for improving human health, for

poverty reduction, as well as for advancing economic opportunity in the world's poorest and most under-privileged regions. And yet, in contrast to other major global issues, the issue of cooking rarely figures at the top of the policy agenda. Fortunately, this is starting to change. Perhaps the most notable change is the recently adopted Sustainable Development Goals, in particular Goal 7, which aims to “ensure access to affordable, reliable, sustainable, and modern energy for all.” (UNDP 2016).

Significant declines in the cost of renewable energy technologies (namely solar PV modules, inverters and battery systems) as well as progress in mini-grid and storage technologies is beginning to make solar the most cost-effective source of new electricity supply in many regions of the world, most notably in rural and remote regions (IRENA 2014; IEA-RETD 2015). This is particularly the case in much of sub-Saharan Africa, where good solar resources are available, and the costs of either diesel systems or of expanding existing transmission and distribution infrastructure is often prohibitive (IFC 2015). As the costs of renewable energy technologies continue to decline, their performance and reliability have continued to improve (IRENA 2014) while new technologies are being developed that could yield yet further breakthroughs such as in the fields of storage, biogas systems, and power-to-gas (P2G).

While attention on improving the sustainability of the cooking sector has begun to increase in recent years, much of the effort to tackle the challenge of sustainable cooking in Asia, Latin America, and sub-Saharan Africa continues to be focused on improving conventional cook stove technologies, promoting the use of pellets from either wood products or agricultural wastes, as well as the overall efficiency of charcoal production (GACC 2016; ECREEE 2015). Even though these improvements are certainly needed, these cooking technologies still rely on wood-based fuels and continue to contribute to a host of problems, including negative impacts on human health, deforestation, soil erosion, and climate change to name a few. In light of the deeper demographic trends in many regions most reliant on firewood and charcoal, continued reliance on wood-based fuels is unsustainable in the medium to long-term.

Objectives of the Report

The report aims to provide an overview of the main technological pathways to fundamentally transform the cooking sector in developing countries to sustainable sources. The report will provide an analysis of the main technological options and provide an estimate of their costs, and feasibility. **One of the primary objectives of**

the report is to inform the political and donor discourse and trigger a much wider policy dialogue about future pathways for the cooking sector. As the cost of renewable energy and storage technologies decreases, technological options are likely to open in the coming years that are not yet part of the international discussion on sustainable cooking options. This relates to a further objective of report, which is **to help policymakers better understand the challenge of achieving sustainable cooking and to suggest concrete steps to drive this transition.**

So far, much of the global energy debate with regard to renewable energy technologies is focused on electricity generation. However, as pointed out above, in many developing countries cooking-related energy use represents over 90% of total primary energy demand. For such countries, attempting to scale up renewable electricity supply without focusing on the cooking sector is therefore thoroughly inadequate, as it leaves much of the energy supply mix as well as many of the most significant challenges untouched. In light of these and many other changes taking place worldwide, it is time to consider how these various technologies could help accelerate the transition toward sustainable cooking.

In order to clarify the path toward implementation, **this report focuses on three (3) different technological pathways and assesses their overall technical viability as well as their scalability.** While the report analyses different technological pathways, it recognizes that a purely “technical” fix alone is not enough. Indeed, all successful technological transitions (e.g. from horses to automobiles, from kerosene lanterns to electric light bulbs) are accompanied by a range of important cultural, administrative, legal, and behavioral changes (Sovacool 2016). Moreover, this report recognizes that in order to be successful, any new technology must be embraced by end-users, it must be both affordable and convenient to use, and its market adoption must scale from the bottom-up on the basis of consumer demand, rather than be introduced or imposed top-down. The track record of top-down initiatives in the fields of development and energy is not particularly encouraging (IFC 2012).

While the report will not be able to provide in-depth answers to all of the challenges it lists, it aims to engage decision-makers critically in this debate and to encourage them to think beyond improved cook stove (ICS) technologies and the continued reliance on wood and charcoal-based solutions; in the process, it aims to explore whether others pathways are possible, and if so, what challenges will need to be overcome for them to become credible, scalable alternatives.

Overview of the Report

Part 1 of the report sets the stage by first defining what is meant by sustainable cooking while providing a brief discussion of why the traditional focus on improved cook stoves does not go far enough.

Part 2 of the report focuses on the tremendous opportunity of transitioning to more sustainable forms of cooking, with a focus on the various health, economic, and environmental benefits that it could bring.

Part 3 of the report provides an analysis of the overall challenge of achieving sustainable cooking, and highlights many of the limiting factors, focusing mainly on sub-Saharan Africa. It also discusses some of the questions and concerns commonly raised when the possibility of cooking with solar, with mini-grid supplied power, or with new technologies like power-to-gas is discussed.

Part 4 of the report contains the main body of the analysis on alternative cooking solutions and examines the three alternative pathways for achieving sustainable cooking. **Section 4.1** examines the potential of solar home systems (SHS) accompanied by storage. **Section 4.2** considers the potential of scaling-up cooking within hybrid mini-grids using a range of technologies, including solar PV, hydropower, wind power, as well as both storage (primarily to stabilize the network) and diesel back-up. **Section 4.3** looks at the potential of distributed biogas solutions, and **Section 4.4** examines the potential of power-to-gas (P2G) distributed in the form of portable cylinders rather than injected into a natural gas pipeline network. In this configuration, power-to-gas fueled by renewable energy sources could provide a way to produce a renewable fuel that could displace reliance on wood and charcoal without needing to rely on electricity, and one that could be integrated directly into existing distribution channels for liquefied petroleum gas (propane).

In examining each of these different pathways, the report provides an analysis of the approximate costs of each technology, the various technical, social, financial, and cultural barriers each pathway faces, as well as an analysis of a number of relevant cultural and behavioral factors that influence the viability of each.

Part 5 of the report provides a synthesis of the key findings, while **Part 6** lays out a five-point action agenda for donors, policymakers and international investors.

1. WHAT IS SUSTAINABLE COOKING?

This report adopts the traditional definition of sustainable development to approach the challenge of achieving truly sustainable cooking. According to this framework, this **means transitioning to a future where cooking needs are met in way that is economically, socially and environmentally sustainable.**³ According to this definition, the continued large-scale use of wood-based fuels is deemed to be unsustainable due to the significant health and environmental impacts associated with wood harvesting and use. While plans are afoot in certain countries (e.g. the Democratic Republic of the Congo) to significantly increase the share of plantation-grown wood in the production of charcoal and firewood in the years ahead, this is unlikely to be sustainable either: not only are the objectives themselves often unrealistic (in the case of the DRC, the target is to replace between 90-100% of total cooking-related biomass use with plantation-grown wood by 2030), they are likely to accelerate already unsustainable rates of deforestation while potentially worsening the food-vs-fuel dilemma frequently faced in the biofuels sector.

Some argue that pellets or other forms of biomass can be made sustainable if the production and harvesting are improved and if more regulation and certification bodies are put in place to oversee the sector. These arguments, however, ignore (or fail to fully appreciate) the sheer power of **demographics**: the population of Sub-Saharan Africa (SSA) is projected to almost triple by 2060, reaching as high as 2.7 billion up from 1 billion in 2015 (World Bank 2015). Given that the overwhelming majority of citizens in SSA continue to rely on biomass to meet their cooking needs (either in the form of firewood or charcoal), **failing to fundamentally change the energy mix in the cooking sector away from biomass all-but-ensures that the rates and extent of harvesting and deforestation will become increasingly unsustainable.** Given the size of the coming demographic boom, **scalable, affordable alternatives to wood-based fuels are needed**, and this will remain the case regardless of how efficient pellet production or cook stove themselves become.

Thus, for the purposes of this report, **plantation-based wood supply, pellets, and other alternatives that rely primarily on wood are not considered a long-term solution to the challenge of achieving sustainable cooking.**



³ This is based on the widely used definition of sustainability that includes social, economic, and environmental dimensions, reflected also in “triple bottom line” framework now in common use to govern investment decisions around the world.

Text Box 1: Why focusing on “improved cook stoves” is insufficient

While much effort continues to be devoted to deploying improved cook stove technologies, this report argues that in order to solve the enormous challenge of sustainable cooking in developing countries, we will have to move beyond these traditional options. Despite significant improvements in recent years, improved cook stoves, when considered collectively, still require huge amounts of charcoal and wood, the harvesting and production of which continue to have significant negative impacts on the environment and on human health. Indoor air pollution is estimated to cause roughly four (4) million premature deaths every year, mainly of women and children (WHO 2016).

While improved cook stoves help mitigate this problem, they do not eliminate it, as the widespread air pollution surrounding densely populated areas such as the “ger” districts outside Ulan Bator in Mongolia or the slums of Abuja illustrate (Bittner, 2016; Hassan and Abdullahi, 2012). In other words, while efficient cook stoves may significantly reduce *indoor* air pollution, they continue to contribute significantly to air pollution in the surrounding area, particularly in regions with high population densities such as urban and peri-urban areas. According to the WHO, the levels of ambient (i.e. outdoor) air pollution are estimated to cause an additional 3.7 million pre-mature deaths each year (WHO 2014; WHO 2015). Furthermore, informal production and distribution structures along the entire value chain of charcoal (even when efficiently produced) still leaves many producers and harvesters vulnerable to economic exploitation, particularly women and children (GACC 2015). On the environmental front, wood harvesting, charcoal burning, transport and trade are in most cases unregulated, making it difficult to obtain reliable data about rates of extraction and consumption. The rampant pace of wood and charcoal consumption for cooking, particularly around the large urban areas such as Lagos (Nigeria), Kinshasa (Democratic Republic of Congo), and Dar es Salaam (Tanzania), is exacerbating unsustainable forestry practices and leading to increased soil erosion, reduced agricultural output, as well as a deterioration in both the quantity and the quality of fresh water (Sanga and Jannuzzi 2005; Hilderman 2010).

And finally, in light of the rapid population growth anticipated in many regions reliant on wood-based cooking, the continued over-reliance on wood-based cooking (however efficiently used) is likely to become less and less sustainable in the long-term simply due to the underlying demographic trends, which will put an increasing burden on forest resources, exacerbate desertification, reduce access to potable water, and further jeopardize long-term prosperity (UNESCO 2012). These concerns are increasingly urgent: in light of the anticipated rate of population growth, rapid deforestation caused in part to meet cooking needs is likely to continue across the region, and this is likely to remain the case even if more efficient cook stoves or charcoal production techniques are utilized.

Thus, this report proposes that **efficient cook stoves and improved charcoal production techniques are best understood as interim measures, rather than truly long-term, sustainable solutions**. Some point to the use of pellets derived from agricultural wastes as a potentially sustainable alternative to firewood and charcoal (Fulland 2016). However, while agricultural wastes remain a valuable resource, they are not present in sufficient quantities in most regions to durably meet local cooking needs, making them a partial solution at best; this issue is likely to remain a challenge for biogas systems as well (see Section 4.3). In light of the importance and urgency of this topic, there is a need to explore the potential for more transformational solutions that move beyond wood or charcoal-based cooking altogether.

Similarly, the use of traditional liquefied petroleum gas (LPG) derived from fossil fuels is also deemed unsustainable in the long-term, first and foremost as it is non-renewable. Beyond the fact that LPG is non-renewable, it is also inherently linked to economic and geopolitical factors, making supply both inherently interruptible and liable to becoming unaffordable, making a significant increase in the reliance on LPG economically unsustainable in the long-term.

If sustainability, as defined by the landmark Brundtland Commission in 1987 as meeting “*the needs of the present without compromising the ability of future generations to meet their own needs*”, remains our long-term goal, the stark realities of the cooking sector for almost half of the world’s population falls far short of what is needed (World Commission on Environment and Development, 1987).

2. THE OPPORTUNITY OF ACHIEVING SUSTAINABLE COOKING



Table 1: Key Facts and Figures

| | |
|-------------|---|
| 93% | Percentage of households in Sub-Saharan Africa rely on wood energy for their daily cooking needs (Cerutti et al. 2015) |
| 3 BILLION | Approximate number of citizens worldwide that relies on open fires and simple stoves using wood, dung, charcoal, and coal to cook their food (GACC 2015). |
| 4.3 MILLION | Premature deaths worldwide associated with household air pollution caused by cooking with traditional fuels like wood and charcoal (GACC 2015). |
| 30% | Share of the population of Sub-Saharan Africa living on less than USD \$1.25/day (World Bank 2014) |
| 1 GJ | Estimated useful energy required per person per year for cooking purposes in Sub-Saharan Africa (Demierre et al. 2014; Sanga and Jannuzzi 2005). This is equivalent to 277.7 kWh of electricity, or roughly the amount of electricity consumed each month by an efficient European household equipped with all modern appliances. |
| 68% | Proportion of households in Sub-Saharan Africa that still do not have access to modern energy services (SE4ALL, 2015) |

Transitioning to sustainable cooking could yield a wide range of benefits to hundreds of millions of citizens around the world, including:

- Improved health and life expectancy through reductions in household air pollution;
- Increased economic opportunity by freeing residents (primarily women and children) from the burden of gathering, preparing, and transporting wood and charcoal products;
- Improved educational outcomes and literacy rates;
- Significant reductions in deforestation, which brings a host of direct and indirect benefits for local communities, including improved water quality and availability;
- Improved resilience against drought and desertification;
- Reduced soil erosion;
- Reductions in greenhouse gas emissions and other harmful air pollutants.

As this short list underscores, many of the benefits of reducing reliance on wood and charcoal-based cooking fuels extend far beyond energy or even climate change, helping address a range of other key international priorities, such as reducing gender inequity, improving child literacy rates, as well as reducing deforestation (SDG 2015).

As such, any analysis of the challenges of achieving sustainable cooking needs to take this complex set of factors into consideration, as the costs and risks of continuing with the status quo are enormous and often under-appreciated. **Transitioning to more sustainable cooking solutions around the world can therefore play a key role in delivering on the global Sustainable Development Goals (SDGs)**, as cooking cuts across many of the key areas of focus.

As described above, this report attempts to critically examine some of the main questions raised about the viability and scalability any alternative pathways to sustainable cooking. The following table provides an overview of a number of questions that frequently emerge.

| COMMON QUESTIONS | SHORT ANSWERS |
|---|--|
| <p>Isn't it more efficient to cook with a primary fuel like wood, rather than first generating electricity which is then converted into thermal form? What about the thermodynamic losses?</p> | <p>This is certainly the case if the electricity is first generated by burning a primary fuel such as coal, natural gas, or diesel. However, with RE technologies like solar and wind, there are no large thermodynamic losses at the beginning of the process, as wind and solar power can be used directly in electrical cooking appliances, and overall conversion losses are small. Also, once installed, the marginal cost of wind and solar is effectively zero, although routine maintenance is still required.</p> |
| <p>Aren't wood and charcoal far more "energy dense" than solar? How can solar ever provide the amount as well as the density of energy required to meet cooking needs?</p> | <p>Energy density is an important challenge. One consequence of this is that large amounts of solar (or wind, or other RE source) are required to produce the same thermal energy as that found in solid fuels like wood, or charcoal. While this remains a challenge, it is beginning to be overcome in part through improved technologies (e.g. storage, P2G), and through the improved efficiencies of cooking appliances. Also, it is estimated that the conversion efficiency of trees at converting sunlight into energy is approximately 1-8% (Hall and Rao 1999), compared to a range of 9% for the least-efficient modules to over 40% for more advanced solar technologies (Green et al. 2015). The main advantage that trees and plants currently have over solar power is that they are far more widespread.</p> |
| <p>Rural residents in many developing countries already struggle to pay for basic electricity services such as lighting and mobile charging, and often do not pay for their cooking fuel, opting to gather wood fuel instead. Won't any electricity-based solution therefore be unaffordable for such low-income residents?</p> | <p>All new energy technologies face an upward challenge to reach wide-scale adoption. Transitioning to more sustainable forms of cooking is likely to require considerable public support and investment, including greater research and development (R&D). As the use of sustainable cooking technologies grows, this is likely to help drive down the costs, which is likely to help make them even more affordable for residents in rural areas.</p> |
| <p>Won't increasing reliance on electricity for cooking significantly increase the total peak demand requirements, which is often concentrated primarily in 2-3 hours of the day, leading to an inefficient over-investment in generation capacity? Can such a massive increase in electricity generating capacity ever be affordable, particularly in rural and remote areas where income levels are low?</p> | <p>Meeting evening demand peaks caused by cooking with either battery storage or with back-up supplies is one of the biggest challenges of electricity-based pathways for achieving sustainable cooking, particularly in mini-grids and for small SHS.</p> <p>In SHS, peak demand can be decreased by using more energy efficient appliances and by potentially storing electricity during the day in order to use it in the evening hours.</p> <p>In mini-grids, efforts have already been made using new signaling technologies to encourage households to slightly shift the timing of their electric cooking in order to maintain the proper and reliable functioning of the mini-grid system and avoid high peak demand because of parallel usage of energy intensive appliances. Such load-management technologies are increasingly the norm in mini-grids around the world and this extends to mini-grids designed to support electric cooking. The aim of such load-management technologies is not to regulate demand patterns strictly or to require users to cook at inconvenient times of the day, but rather to provide signals to residents in rural areas to inform them when supply is more limited (e.g. when the battery bank is low) and when it is more abundant.</p> |
| <p>Isn't power-to-gas (P2G) far too expensive and complicated to be used in a context such as SSA?</p> | <p>While the technology to produce synthetic methane is itself complicated, the same may be said for automobiles, welding machines, or a number of other appliances commonly used in rural or peri-urban regions. The important point is that the end product is not, and in the case of cooking gas, it is already in wide use throughout SSA and large parts of Asia in the form of liquefied petroleum gas, or LPG. If the business case for P2G can be made investable by making the end product cost-competitive with other alternatives like LPG and charcoal, the complexity of production should not pose a significant barrier to scale-up.</p> |

In order to better organize the various technological pathways and potential policy interventions, this report distinguishes between urban areas, peri-urban or near-grid areas, as well as rural and remote areas. The figure below provides an overview of these three regions:

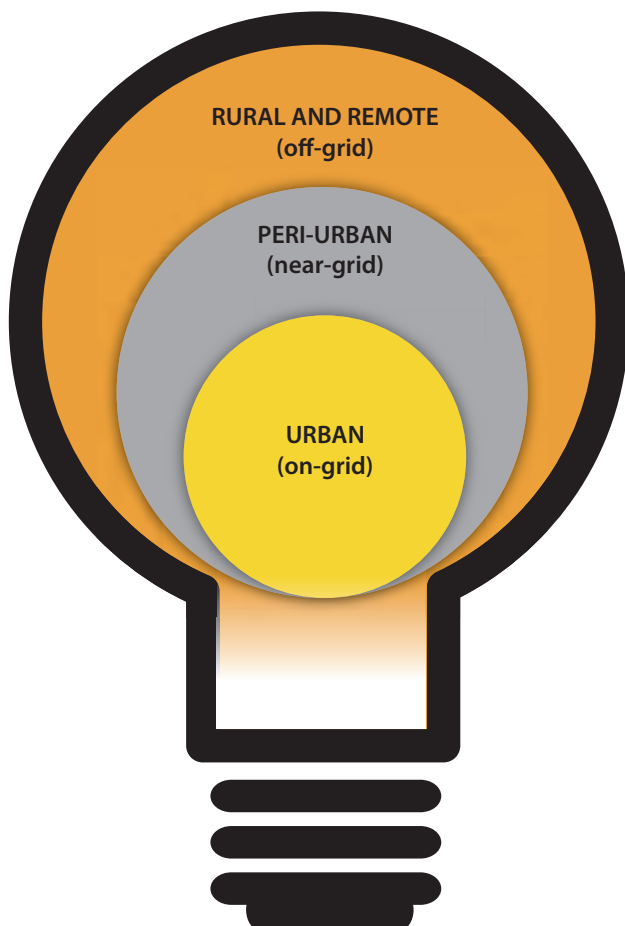


Figure 1: Categorization of Three Key Regions with Different Cooking Needs and Realities

Distinguishing between these three key regions is important, as the various benefits as well as the various policy and technological interventions required to create them are also likely to look different depending on which region is targeted. For instance, citizens living in urban areas may have a higher willingness or ability to pay as well as greater access to alternatives, potentially making it easier to encourage large-scale substitution.⁴ In contrast, many rural and remote regions where there is little to no electricity access and considerably lower willingness to pay, making it more

difficult to encourage large-scale substitution. In addition, the cost of new technological solutions (e.g. electricity-based cooking pathways or power-to-gas pathways) may be more expensive to deliver in rural and remote regions, widening the gap that needs to be bridged in order to make alternative cooking solutions widely adopted by local residents, who are the ultimate end-users of cooking technologies.

In order to sharpen the focus, this report focuses primarily on rural (off-grid) and peri-urban (near-grid) areas, rather than in urban centers, though some of the solutions explored could also be applicable in urban areas, while some (such as renewably-powered P2G) could even be better suited to areas with higher population densities.



⁴ However, despite easier access to alternatives, this is not always the case: in certain urban areas such as those in Tanzania, charcoal use has continued to grow rapidly despite the presence of alternatives (TATEDO 2016).

3. UNDERSTANDING THE CHALLENGE

Despite the many benefits listed above, a number of crucial barriers continue to stand in the way of a sustained scale-up beyond unsustainable wood-based cooking. This section is broken down into four different sub-sections that serve to set the stage for rest of the report: the first examines the various negative effects associated with continued reliance on wood and charcoal for cooking (3.1.); the second focuses on better understanding the barriers to sustainable cooking (3.2.); the third provides an overview of the different cooking appliances available as well as the total approximate energy needs associated with each technology (3.3.); and the fourth outlines the methodology used to quantify cooking-related energy needs (3.4.).

3.1. Negative Effects of Cooking with Wood and Charcoal

In order to understand the case for accelerating the transition to more sustainable cooking, it is important to consider the various negative effects of continued reliance on the primary existing fuel sources, namely, wood and charcoal. This section considers seven (7) different negative effects.

Wood Consumption:

Sub-Saharan Africa continues to have the highest average per-capita wood consumption in the world, with an estimated 0.69m³/year (Cerutti et al. 2015). Estimates for highly forested countries like the Democratic Republic of the Congo (DRC) are closer to 1 m³/year (Mayaux et al. 2013). This compares to a global estimated average of 0.27m³/year. According to surveys undertaken in Tanzania, which is currently believed to be the largest charcoal producer in sub-Saharan Africa, it is estimated that on current trends and in the absence of direct government intervention, virtually all of Tanzania's publicly-owned forests will be depleted by 2028 (Mwampamba 2007). The sheer rate of cooking related wood consumption, when combined with anticipated population growth, makes the concerns over deforestation real, and increasingly urgent.

Moreover, since most fuel wood used for cooking in Sub-Saharan Africa is not purchased, but gathered from the surrounding environment, this makes it more challenging to introduce alternatives into the market, as the benchmark price of gathering fuel wood is effectively zero. This singular fact poses a unique challenge, particularly in the regions most reliant on fuel wood for their cooking needs, as it is in these regions where the ability or willingness to pay are typically the lowest.

Environmental Impacts:

Reliance on wood and charcoal for cooking has a number of well-recorded negative effects, including deforestation, soil erosion, loss of many critical ecosystem services, loss of biodiversity, loss of food sources from indigenous plants and animals, etc. (GEF 2013; Sanga and Jannuzzi 2005; Hilderman 2010; UNESCO 2012). Compound these various impacts is the fact that most areas deforested for either firewood or charcoal production are rarely replanted, resulting in further negative impacts while undermining local ecosystems' capacity to recover (Chaix, 2010).

Human Health Impacts:

Health impacts from poor air quality include a wide range of issues including increased infant mortality, reduced life expectancy, pulmonary and other respiratory diseases, as well as a heightened risk of cancer (WHO 2016; GACC 2015). Out of the estimated 4.3 million pre-mature deaths per year globally caused by indoor air pollution associated with cooking with wood and related fuels, 12% are due to pneumonia, 34% from stroke, 26% from ischemic heart disease, 22% from chronic obstructive pulmonary disease (COPD), and 6% are estimated to come from lung cancer (WHO 2016).

Gender Inequality:

Recent data suggest that men and women over fifteen (15) years of age spent between eight (8) and nine (9) hours per week collecting wood to meet their household cooking needs (World Bank 2006). Women and in particular children remain exposed to much of the negative health impacts of cooking due to high levels of indoor air pollution.

Opportunity Costs:

There are significant negative economic consequences and tremendous opportunity costs of spending so many hours engaged in gathering and transporting wood and/or charcoal. In some villages in western Tanzania, for instance, residents travel up to 10km per day to collect wood (Mwampamba 2007). This underscores the significant opportunity cost of gathering traditional biomass for cooking purposes: if women and children are out gathering wood, this limits their opportunities to go to school, improve their education, or engage in other more productive activities. This restricts literacy among the young and significantly harms long-term

economic prosperity. Thus, lifting the burden that gathering firewood imposes on residents, particularly those in rural and peri-urban areas, could significantly assist in lifting millions out of poverty both by improving their health, as well as by freeing up their time.

3.2. Barriers to Transition

There are many crucial challenges that continue to limit the uptake of new and more sustainable cooking technologies. These include:

- A number of **cultural and behavioral barriers** linked to cooking habits, traditions, and preferences (Goodwin et al. 2014);
- **High upfront cost** of alternatives, including both the cooking appliances themselves (the stoves or ovens) and the costs of procuring the energy required to run them (i.e. paying for the gas, the electricity, or the pay-as-you-go plan) (GEF 2013);
- The **availability in many regions of zero-cost fuel wood**, gathered by residents directly from the surrounding environment, which hampers the adoption of alternatives and impedes substitution (Schlag and Zuzarte, 2008); it is estimated that only some 50% of households in Sub-Saharan Africa pay something for their cooking fuels, with the remaining 50% gathering firewood directly from the surrounding area (Leach and Oduro, 2015);
- **The risk of reversion**, which occurs when residents revert to traditional cooking technologies even though cleaner options are available, typically due to cost, preference, or other factors;
- **Low income levels**, which make it difficult to finance and support the market uptake of more sustainable solutions, particularly for lower income residents, or those at the bottom-of-the-pyramid;⁵
- **Lack of familiarity** with (and occasionally even resistance to) the use of new technologies;
- **The remoteness** of many regions reliant on wood and wood-based fuels for cooking, which increases the cost and logistical challenges of delivering interventions.

⁵ The term « bottom of the pyramid » refers to the portion of the global population with the lowest average income levels.

As the above lists highlights, the barriers facing the uptake and diffusion of more sustainable cooking technologies are significant and in many cases, difficult to overcome. Foremost among these barriers are **cultural and behavioral factors**: cooking choices and behaviors are deeply tradition-based and location-specific, making it difficult to drive large-scale substitution in the market, while also limiting the potential scalability of alternatives (Goodwin et al. 2014; Leach and Oduro 2015). Overcoming both the cultural barriers as well as the underlying economic barriers of cooking in developing countries presents a formidable challenge. **Cooking is deeply embedded in people's way of life, and is woven into the very fabric of communities**, which means that communities are likely to remain more resistant to change than they might be with other innovations such as the advent of mobile technologies (Goodwin et al. 2014). Thus, any effort to scale-up alternative cooking solutions needs to be based on a sound analysis of what actually drives the adoption and diffusion of new technologies. Behaviors often run deep and the cultural and other social factors surrounding the question of cooking make this uniquely so with sustainable cooking.

Recent examples of rapid adaption of new communication tools such as smart phones in areas where not even landline phones existed suggests the transition to the widespread adoption of new technologies can be quite rapid, provided the right conditions are in place.⁶ Key among these conditions are strong customer demand, the presence of significant and tangible benefits over alternatives, and the product being available at an affordable cost. The question of cost is important in two different senses: both the **upfront cost**, as well as the ongoing, **usage-related cost**.

As Adkins et al. show for both Tanzania and Uganda, the willingness to invest in more expensive (though significantly more efficient) cook stoves dropped dramatically when the price rose from USD \$10 per unit to \$17.5 per unit (Adkins et al. 2010). This suggests a significant customer reluctance to spend much more than USD \$10 per stove, and points to an important insight for any successful interventions in the cooking sector: **the business model used to scale up the use of the new technology must strive to make the technology affordable from the outset, as well as on an ongoing basis.**

Making new cooking technologies affordable to residents, particularly those in rural and remote regions where income levels are quite low, may therefore require bundling the cost of

⁶ There is, however, an important difference between cleaner cooking technologies and mobile phones, namely, that there is currently no alternative to communicate remotely with friends, colleagues, or family members other than via a mobile phone. By contrast, there are many different ways of cooking (Fulland 2016).

the technology and/or cooking appliances into an affordable, flat (e.g. monthly) payment in order to circumvent the high upfront cost barrier, and in order to ensure that the actual costs of using the technology remain affordable. Failure to do so increases the risk that residents will revert to their previous cooking behaviors as soon as economic or social circumstances change. This points to the need either for targeted support (e.g. subsidies) or customized financing solutions that allow end-users to amortize the cost of both the cooking appliances themselves, as well as the systems (or cylinders) used to power them.⁷

A further critical factor is the **low income levels** in many of the regions most reliant on traditional cooking fuels. It is often the lowest-income countries in Sub-Saharan Africa, for instance, that have the highest reliance on wood and charcoal for their cooking needs (Leach and Oduro, 2015). Over twenty (20) countries in Sub-Saharan Africa, for instance, have more than 50% of their populations living on a daily income level of less than USD \$3.10 per day, considered by the UN and the World Bank the threshold for those living in poverty (World Bank 2016). In such countries, many of the poorest citizens live in rural or in peri-urban regions and often do not have the income required to afford significant changes in their cooking habits, even if such changes would bring significant benefits for their family health and future economic prospects. Thus, **developing interventions, policies, or investment plans to support the transition to sustainable cooking technologies in these regions has to be designed to work in an environment with low income levels, and with a correspondingly low willingness to pay.**

A further problem complicating the situation is that research shows that most households do not fully “substitute” from one fuel to another, as was previously implied by the traditional “energy ladder” model of development, but instead combine different fuels for different purposes in a process known as “fuel stacking” (IEA 2006). Modern forms of energy such as electricity are typically used very sparingly at first and are only used for particular services such as radio or watching television, while other fuels such as LPG might be used to boil water, and charcoal might be used to cook traditional dishes. Moreover, research suggests that people are likely to switch away from both cooking and heating last, the two single largest sources of household energy use (IEA, 2006). For instance, in Nigeria and Ghana, two of the countries

7 An example of this that has begun to emerge in certain regions is a business model in which pellet producers are beginning to offer residents the option of signing up for a “cooking service contract” that combines the use of a stove and a monthly supply of pellets for a flat monthly rate (Fulland 2016). New business models like this could play an important role in accelerating the adoption of more sustainable cooking technologies (see World Bank 2014).

with the highest rates of electrification in West Africa, 60 to 70% of the population continues to rely on either charcoal or wood for their cooking needs. This figure rises to over 90% for countries like Liberia and Sierra Leone.

Indeed, relying on multiple fuels can provide a sense of energy security: relying primarily or exclusively on only one fuel source is likely to leave households vulnerable to sudden disruptions of supply, or rapid increases in price. As has been pointed out in a recent landmark report, “*As incomes increase and fuel options widen, the fuel mix may change, but wood is rarely entirely excluded.*” (World Bank 2014).

It is important to underscore that **the choice of cooking technologies is rarely if ever driven strictly by economic considerations**: as pointed out above, a range of factors including convenience, history, individual habits, and local culture play a significant role (Hosier et al. 1987; Jones 2015; Zulu et al. 2013). Thus, sustainable cooking technologies must be well adapted to individual communities’ way of life, and must be able to be easily integrated with existing cooking habits. This means that the transition to other fuel types, whether electricity or otherwise, is likely to be a gradual process; this underscores the need to accelerate this transition now.

3.3. Overview of Cooking Appliances

A further factor that is critical to understand in order to understand the challenge of achieving sustainable cooking is that the primary energy sources used are only part of the problem: there is also the actual technology or device used to convert that energy into a usable form. In this sense, the actual energy efficiency of the cooking device plays a critical role, and can be an important factor in improving the affordability of sustainable cooking solutions.

There are three main types of cooking appliances:

- **Electric:** These can be used either with the SHS pathway or under the mini-grid pathway, as well as in urban and peri-urban areas where there is sufficient access to electricity; this includes both hot plates and hot coils as well as newer, and more efficient induction hotplates. The newest models available for electric hotplates range from 800W to 2300W and feature a price range of between EUR 10 and EUR 100 (Thetford Europe 2015; Konga 2016). A recent survey of appliances in this category reveals an average of 1295W.⁸ Other reports confirm the availability of electric cooking

8 See: <http://hot-plates-review.toptenreviews.com/>

appliances in the EUR 12-20 range in key markets in Sub-Saharan Africa such as Tanzania, Kenya, Nigeria and Ghana (Leach and Oduro 2015). The average efficiency of such traditional hotplates and electric coils is 70%. More innovative technologies, such as induction hot plates are also available in certain markets but they are priced at a significant premium, ranging from EUR 45 to EUR 95, depending on the make and model. Induction hot plates feature a total efficiency of up to 90%.⁹

- **Gas based:** these stoves consist of a gas burner that can be supplied with different gas-based fuels, including kerosene, LPG, and natural gas. These stoves are widely available in key markets and have a price range of between EUR 20 – 85 (Konga, 2016). The conversion efficiency of natural gas or LPG use when used in a standard gas stove for cooking ranges from 50-60%.
- **Solid fuel based** (wood, dung, pellets, and charcoal): Many households continue to rely on cooking with three stones, positioned to hold a pot directly above the fire or burning coals. Traditional cook stoves range in cost, but most are available for only a few Euros or may be built directly by end-users. Improved cook stoves, however, have a wider price range, and can be priced at between EUR 5 for basic models and EUR 65 per stove for the most advanced (World Bank 2011). The efficiency of cooking with solid fuels ranges widely depending on a range of factors including how dry the fuel is, the design of the cooking stove, as well as the ambient environment (wind, etc.); it is assumed to range from 5-20% for conventional firewood, and from to 20-50% on the high end for more efficient charcoal and pellet-based stoves.

Next to purchasing the modern cooking equipment, the fuel or energy input costs for each option are critical.

There is limited data available on the costs (and energy demand) of cooking appliances in the African market. Due to the limited market for DC appliances, they are generally more expensive than standard AC appliances (Global LEAP, 2016). However, cost reductions for DC appliances can be expected for the future as the market for these products continues to grow. The table below provides an overview of the main categories of electric appliances available as well as the approximate daily energy consumption per household of each different cooking approach:¹⁰

9 See: <http://hot-plates-review.toptenreviews.com/>

10 For conversion factors, see Figure 5 in Part 5 below.



Table 3. Basic Data on Cooking Technologies and Energy Use

| Appliance | Cost of the Stove (in EUR) | Watts (Range) | Approximate Daily Household Consumption (in Wh/d for electric options, or in kg/day for solid and gas-based fuels) | Daily Consumption (Wh/d or Fuel use per household, in kg/day) |
|--|----------------------------|---------------|--|---|
| Three Stones (Wood) | 0 | N/A | 4.15 – 20.76 kg/d | 68.48 – 342.54 MJ |
| Traditional Cook Stove (Wood) | 0 - 5 | N/A | 3.32 – 8.3 kg/d | 54.78 – 136.95 MJ |
| Improved Cook Stove (Wood) | 5 - 65 | N/A | 2.08 – 5.53 kg/d | 34.32 – 91.25 MJ |
| Three Stones (Charcoal) | 0 | N/A | 1.92 – 4.81 kg/d | 54.72 – 137.09 MJ |
| Traditional Cook Stove (Charcoal) | 0 - 10 | N/A | 1.6 – 4.01 kg/d | 45.60 – 114.29 MJ |
| Improved Cook Stove (Charcoal) | 5 – 65 | N/A | 1.2 – 2.4 kg/d | 34.20 – 68.40 MJ |
| Improved Cook Stove (Wood-based Biomass Pellets) | 16 – 80 | N/A | 1.76 – 3.96 kg/d | 30.41 – 68.43 MJ |
| Improved Cook Stove (Agro-waste Pellets) | 16 – 80 | N/A | 2.42 – 5.44 kg/d | 30.49 – 68.54 MJ |
| Slow cooker / rice cooker / crock pot | 70 - 130 | 250 – 300 | 500 – 600 Wh/d | 1.8 – 2.16 MJ |
| Small Electric Oven | 40 - 70 | 500 – 1000 | 500 – 1000 Wh/d | 1.8 – 3.6 MJ |
| Single Burner Hot Plate | 8 - 35 | 600 – 1500 | 1200 – 3000 Wh/d | 4.32 – 10.8 MJ |
| Double Burner Hot Plate | 16 - 70 | 800 – 2300 | 1600 – 4600 Wh/d | 5.76 – 16.56 MJ |
| Induction Hot Plate | 45 - 95 | 1200 – 2300 | 2400 – 4600 Wh/d | 8.64 – 16.56 MJ |
| Microwave Oven | 50 - 100 | 600 - 1200 | 100 – 1200 Wh/d | 0.36 – 4.32 MJ |
| Gas Stove (single burner) | 20 – 60 | N/A | 0.3 kg/d | 13.7MJ |
| Gas Stove (double burner) | 30 - 90 | N/A | 0.3 kg/d | 13.7MJ |
| Gas Stove (four burner) | 40 - 100 | N/A | 0.3 kg/d | 13.7MJ |

Sources: Atteridge et al. 2013; World Bank 2011; http://www.biomassenergycentre.org.uk/portall/page?_pageid=75,20041&_dad=portal; Lotter et al. 2015; IEA 2006; Various Internet sources and manufacturers for the cooking stoves; note that these prices may differ by location, and may be costlier in certain regions than in others. Assumed energy density ratios: Firewood = 16.5MJ/kg; Charcoal = 28.5MJ/kg; Wood pellets = 17.28MJ/kg; Agro-waste pellets = 12.6MJ/kg; LPG = 45.9MJ/kg. Conversion ratio for electricity = 3.6MJ/kWh. For the ranges of stove efficiencies see Table 10.

3.4. Quantifying Annual Cooking-Related Energy Needs

It has been estimated that the total annual cooking-related energy needs per person is 1GJ (Sanga and Jannuzzi 2005; Demierre et al. 2014). This figure of 1GJ per person per year will provide the basis for most of the cost analyses included in this report. While some reports adopt a lower estimate for per

capita energy needs, **the actual magnitude of the cooking needs is ultimately less important** (for analytical purposes) **than the fact that it provides a common basis of comparison across all technologies.**

Based on technology-specific assumptions for each of the different cooking pathways examined, it is possible to estimate the total cooking-related energy needs for a wide range of different energy sources and associated cooking

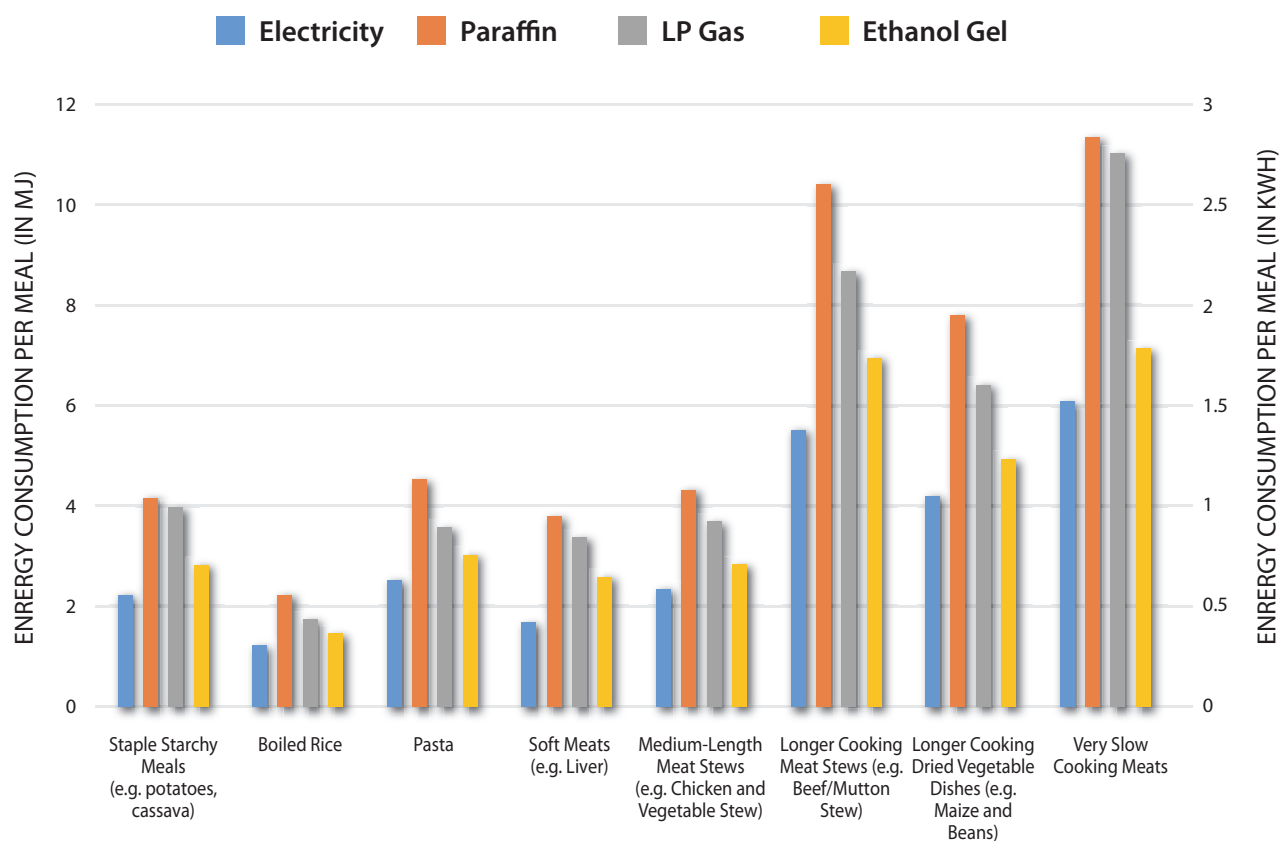
technologies. Thus, if the cook stove used is only 10% efficient, for instance, the total primary energy required per person increases to 10GJ. And if an electric cooking appliance is only 70% efficient at converting electrical energy into heat, then meeting an annual energy need of 1GJ requires 1.43GJ of energy input, which translates into approximately 397kWh (1GJ = 277.7kWh).

However, this 1GJ per person per year is inevitably a simplification, as it hides important regional and cultural differences, including the average energy-intensity of the meals being cooked. Indeed, the energy required to cook

each individual meal varies widely, and will play a significant role in determining the total energy needs (and total system size requirements) for any energy-related infrastructure that is provided to meet this cooking need (Cowan 2008; Batchelor 2015).

The figure below provides an overview of the main meal types and the total energy requirement to cook them in MJ. The data have been adapted to represent the per-meal energy consumption for a household of five using four different cooking fuels.

Figure 2: Per-Meal Energy Consumption for a Household of Five (Left Axis = in MJ; Right Axis = kWh)



Source: Adapted from Cowan 2008

Thus, the types, size, as well as the frequency of meals cooked will have a significant impact on the total average energy (or electricity) needs in a given village or region, and thus will impact the total system size required (in the case of solar PV or mini-grids). This is one reason why global comparisons of the cooking sector are inherently difficult, as regional

differences even within countries are sometimes quite large in terms of the most common meals cooked. As a result, this report relies on broad ranges of energy consumption per household, as well as a range of appliance efficiencies in order to arrive at comparable figures for each of the pathways examined.

4. MAIN TECHNOLOGICAL PATHWAYS FOR ACHIEVING SUSTAINABLE COOKING

This section will outline a wide range of different potential technological pathways to replace traditional biomass-based cook stoves, including solar home systems, hybrid mini-grids, and power to gas (P2G). **The reason that this report focuses on these technologies as opposed to more common cooking alternatives such as solar cookers and solar water heaters is that they are seen to have greater overall potential to significantly accelerate the transition to sustainable cooking.** Solar cookers and other technologies have a number of limitations, including social, cultural and weather-related, that make it unlikely that they will ever significantly transform cooking behavior. Thus, this report focuses instead on technologies that are believed to have greater long-term viability and scalability.

For each different energy source used to meet cooking needs, there is a range of different cooking appliances, as seen in the table above. While there are hundreds of different cooking

appliances from a wide range of different manufacturers, each with unique specifications and cooking efficiencies, this report attempts to provide a broad overview by drawing on ranges and industry averages. **At the heart of this analysis is the assumption that the total average useful energy per person for cooking purposes is 1GJ per year** (Sanga and Januzzi, 2005; Demierre et al., 2014). While cooking needs differ due to a range of factors, including most notably a person's age, and the energy-intensity of the meals cooked, this number is widely accepted as an average figure for per capita cooking-related energy demand. As such, this number is used to derive the various cost ranges provided for each of the pathways below, based on the actual efficiency of the cooking appliances themselves (e.g. electric coil vs. induction hotplate).

As a benchmark, it is helpful to draw on the current ranges for firewood and charcoal:

Table 4: Actual Cooking Energy Demand and Costs for Firewood and Charcoal¹¹

| Cooking Fuel | Actual Primary Energy Demand per Person for Electric Cooking (Range in kg), per person per year | Cost Range of Supplying 1GJ of Cooking Energy | Approximate Cost Range, per person per year |
|--------------|---|---|---|
| FIREWOOD | 2.5 – 20GJ (approximately 151kg – 1 212kg)* | EUR 0.0 – 9.10 | EUR 0 – 182 |
| CHARCOAL | 2.5 – 10GJ (approximately 88kg – 350kg) | EUR 3.51 – 17.55 | EUR 8.78 – 175.50 |

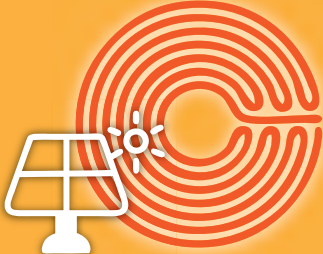


* The low end of the range assumes that the cost of gathering wood is zero; the high end of the cost range represents a firewood cost of EUR 0.15/kg. It is important to note, however, that the upper end of the cost range shown here would rarely ever be attained, as most households gather a portion of their own firewood, and few pay a rate as high as EUR 0.15/kg at all times. The energy conversion rate for wood is assumed to be EUR 60.6kg/GJ, or 16.5MJ/kg.

11 Assumptions: Cooking efficiencies range from 5% for the basic three-stones configuration up to 50% for efficient charcoal stoves. Cost of firewood ranges from 0 (for wood that is simply gathered from the surrounding environment) to EUR 0.15/kg for dried wood. The cost of charcoal ranges from EUR 0.06/kg to EUR 0.29/kg. The energy density of firewood is assumed to be 16.5MJ/kg while that of charcoal is assumed to be 28.5MJ/kg.

4.1. Solar Home System Pathway

Description of the pathway

Table 5: Actual Cooking Energy Demand and Costs for Solar Home Systems

| Actual Primary Energy Demand per Person for Electric Cooking (Range in kWh), per person per year | Approximate Levelised Electricity Generation Cost from a SHS (Equipped for Cooking Purposes, Range in EUR/kWh) | Approximate Cost Range, per person per year (EUR) |
|--|--|--|
| <p>1.11 – 1.43GJ (308kWh – 397kWh)</p>  | <p>EUR 0.40 – 0.90/kWh</p>  | <p>EUR 123 - 357</p>  |

Solar home systems (SHS) are widely used in rural areas around the globe to provide electricity directly to households. SHS typically involve a solar PV array, a small battery bank, an inverter, wiring, a power socket to charge mobile phones, etc., as well as a few basic electrical appliances such as light bulbs. The market for SHS is growing rapidly in many parts of the world and has become a cost-competitive means of providing electricity, notably in rural and peri-urban areas. In Bangladesh alone, 3.2 million SHS have been installed in the last few years (IRENA 2015). In Africa and Asia, about 89 million people have access to electricity services by using off-grid solar products. By 2020, it is estimated that an additional 100 million households could be reached (Global LEAP, 2016).

SHS are stand-alone PV/battery systems used for a range of small and medium-sized appliances most commonly used in off-grid or near-grid areas. Traditionally, SHS only fulfilled the very basic electricity needs of a remote household, such as lighting, radios and mobile phone charging, though larger SHS systems can be designed to power significantly larger loads as well, though at a significantly higher cost. In most SHS direct current (DC) power is used in order to avoid losses when converting DC power from solar systems into AC. SHS typically operate at a voltage of 12 V and run for 3 to 5 hours per day; when connected with storage systems (as is almost universally the case) SHS can provide power around the clock.

Current and projected cost of cooking with a SHS

The total size and cost of SHS is a direct function of the total energy demand that needs to be met: buildings or households with a high energy demand will require a larger PV array, a larger battery storage system, as well as larger wiring and inverters to accommodate the higher power demand. Due to the high wattage of most cooking appliances, which range from 600W on the low end to over 2300W on the high end, the actual system configuration will depend to a significant degree on which appliances are used. A further important factor is the kinds of meals that are cooked (see Figure 2 above).

It has recently been estimated that the combined cost of a SHS equipped to meet household cooking needs ranges from EUR 925 – EUR 5,560, depending on a host of factors (Leach and Oduro, 2015). This range includes the larger size of the solar PV system, the larger battery bank, a range of different appliance efficiencies and consumer habits, as well as the appropriate inverter and wiring to meet cooking-related electric loads. On the lower end, a system configured at the lower end of the cost range is estimated to supply a total daily electricity consumption of 1,431Wh, which is likely sufficient to meet a portion of a household's cooking needs, while the rest continue to be met with traditional means (i.e. firewood or charcoal); on the higher end, a daily electricity consumption of 4.151Wh, which is closer to reflecting the total cooking needs of a typical household.

However, it is important to note that the initial cost number cited above only reflects the initial cost of system: in particular, it does not cover the cost of battery replacement, which ranges from a few hundred EUR to approximately EUR 1.000 and is scheduled to take place every two to five years, depending on usage patterns and overall performance. When the total costs of meeting cooking needs over a 20-year period are considered, including battery replacement and general maintenance, the total costs range from EUR 1.590 – EUR 19.275 per household (Leach and Oduro, 2015). For rural households with average incomes of less than EUR 1.000/year, these costs are high indeed and are likely to discourage many residents from relying on electricity for cooking purposes until costs become more affordable, or subsidies bring them more in line with other options such as charcoal, pellets, biogas, or LPG. However, as seen below, there are a number of areas in which further technological improvements could transform the sector.

In order to openly compare the costs of different cooking technologies, this report draws on the framework set out by Sanga and Januzzi, 2005 and Demierre et al. 2014, in particular the assumption of an average cooking-related energy need of 1GJ per person per year. Based on efficiencies of 70% for standard electric hotplates and 90% for new induction hotplates, this translates into a total energy demand per person of between 1.11GJ and 1.43GJ per year. Converting this into

daily electricity needs, this translates into **between 0.84kWh and 1.09kWh per person per day**¹². Note that this represents a generic average, and that individual energy demand may be significantly higher or lower based on local circumstances, as well as actual cooking habits, the energy intensity of the meals cooked, as well as the overall cooking behavior of the user (see Leach and Oduro 2015).

At the heart of the cost analysis for cooking with SHS is the estimated range for the levelized cost of electricity. Given the significantly larger battery requirements than for a standard SHS equipped to provide lighting and basic services, as well as the likelihood of needing multiple battery replacements over the course of the system's life, **this report assumes a range from EUR 0.40/kWh up to EUR 0.90/kWh for the levelized cost of electricity generation from a SHS.**

As can be seen from the table below, adding cooking appliances can considerably increase the required system size of a SHS, making it by far the largest single source of demand. The high demand and wattage of electric cooking appliances represent perhaps the single greatest challenge of adding them within SHS or mini-grid systems, as they lead to a significant increase in the total system size requirements, as well as increase the eventual wear-and-tear of system components, most notably of the battery units.

Table 6: Standard electric appliances for SHS, cooking appliances and watt

| | Watt min | Watt max | Watt-hours per day (approximate) ¹³ |
|-----------------|----------|----------|--|
| Lighting | 1 | 5 | 15 |
| Mobile charging | 2 | 7 | 3 |
| Laptop | 20 | 100 | 150 |
| Television | 8 | 10 | 150 |
| Fans | 8 | 10 | 200 |
| Refrigerators | 30 | 40 | 1000 |
| Cooking | 600 | 2300 | 1200-4600 |

Sources: Amol A et al., 2015; Global LEAP, 2016; Leach & Oduro, 2015

While these numbers are quite high, and translate into a significant cooking-related expenditure that many individuals in rural areas in particular are unlikely to be willing to make, it is important to note that **there is a substantial technical potential for reducing this total daily energy demand by improving both conversion efficiency and reducing the**

¹² 1GJ = 277.77kWh; 365 days per year.

¹³ Based on average hours of use: 3 Watt mobile phone charging, 2 hours; 1 W/150 lumen lighting, 15 hours; 30W 19" LED TV, 5 hours; 40 W 12" Table Fan, 5 hours; 100 W fridge (60-80 litres), 10h. (Source: LEAP 2016).

total wattage required for cooking appliances. There are three main drivers for SHS cost reductions:

1. **Cost reductions of system components**, including PV modules, inverters and batteries;
2. **The use of more efficient appliances**, which can significantly reduce the total size (and cost) of the PV/battery system required to deliver the same level of service (e.g. LED light bulbs instead of traditional incandescent bulbs);
3. **Reductions in soft costs**, including improved logistics, better customer acquisition, economies of scale, and quicker project installation.

Previously, the largest cost component of SHS was the PV module. However, in the past five years, the costs for solar modules was reduced by about 80% (Ferroukhi et al.,

2014). Consequently, the solar modules now account for approximately 25% of total costs of off-grid SHS, and this share is projected to decline further in the years ahead (Amol et al., 2015). Moreover, recent research suggests that the use of high-efficiency appliances in other areas of household energy use such as refrigerators, televisions, and light bulbs can reduce the total cost of solar home systems and their associated appliances by 50% or more, depending on the particular system configuration (Amol et al., 2015).

Figure 3 below shows the past and expected cost development of SHS between 2009 and 2020 for a system that can provide 4 hours of light, four hours of television (19" TV), six hours of radio and one mobile phone charge per day. Although cost reductions in system components (PV modules and batteries) will remain an important driver for further cost decline, the role of more efficient appliances and improved delivery systems (including new business models) is likely to grow in importance.

Figure 3: Cost of a SHS for Basic (i.e. non-cooking) Household Electricity Needs



Source: Based on Global LEAP, 2016

The figure above underscores two important insights: first, that the costs of solar home systems (including batteries, wiring, inverters, etc.) are expected to continue to decline significantly in the years ahead; and second, **the efficiency**

of the end-use appliances plays a critical role in reducing total system costs, as each individual household needs a smaller PV array and battery bank to provide the same level of service.

Challenges:

The list below provides an overview of some of the key challenges facing the SHS cooking pathway:

Limited Potential for Major Improvements in Appliance Efficiency:

While improvements in the efficiency of lighting (namely through LED technologies) have been significant in recent years, it remains unclear how much further existing cooking appliances can be improved in terms of efficiency, as most electric cooking appliances are already fairly efficient in converting electrical energy into thermal energy and are considered fairly mature (70% efficiency is common) (Ravindranath & Ramakrishna, 1997). The primary source of improved efficiency for cooking-related appliances in recent years has been with the emergence of induction stoves, which can have a conversion efficiency of up to 90%. However, induction stoves range from EUR 50-100 for a single plate, which is anywhere from two to eight times more expensive than the standard electric hotplate available in most markets.

Thus, the potential for continued dramatic cost declines due to improved electric cooking *appliance* efficiency arguably remains limited. This suggests that the bulk of future efficiency and cost improvements is likely to come from either from improvements in battery costs and performance, as well as in reducing the overall system delivery costs (i.e. soft costs) through improved logistics, innovative business models, economies of scale, better customer acquisition, and more rapid installation and customer service.

High Upfront Capital Cost:

Another commonly cited challenge is the generally high upfront capital cost, which has historically acted as one of the leading barriers to the successful roll out of renewable energy technologies (Jacobs et al. 2016). In addition, the ability to pay for the PV-battery systems sufficiently large to accommodate electric cooking appliances, which ranges from approximately EUR 925 to EUR 5.560 according to Leach & Oduro, 2015) might be too high for most residents in rural communities, particularly without public subsidies to reduce upfront system costs. Indeed, **the high costs and capital intensity of equipping households with solar and battery systems equipped to meet cooking needs is likely to remain a persistent challenge for the widespread adoption of SHS-based cooking.**

However, innovative finance mechanisms have been developed in the past years, including pay-as-you-go (PAYG) mechanisms that make it possible for users even in rural and

remote regions to afford systems by making regular monthly payments. Such business models are likely to provide an important means of increasing access to sustainable cooking solutions in the years ahead, building on their success in providing lighting and meeting basic electricity needs.

Reversion Risk:

A notable risk remains, however, that if the ongoing operating costs of cooking with electricity remain too high, residents may be inclined (or driven) to revert to relying on traditional cooking fuels instead of continuing to use their SHS for cooking purposes. As long as the costs of electric cooking remain markedly higher than firewood, charcoal, pellets, or other similar options, encouraging rural residents to adopt and stick with electric cooking is likely to prove difficult. Analysis from the World Bank indicates that the displacement rate for solar systems (namely, the rate at which traditional fuels are displaced by the new technology in practice) ranges from 10-40% (World Bank 2014). Whether this will improve over time as residents gradually become more familiar with electric cooking remains to be seen. **Thus, the continued availability of cheaper alternatives, combined with the persistence of traditional technologies and habits, are likely to continue to pose a significant challenge for SHS-based electric cooking pathways' ability to fully displace reliance on conventional fuels such as firewood and charcoal.**

Shortened Battery Life:

A further challenge is that the use of cooking appliances in SHS can have a negative effect on battery life; the deeper a battery discharges, the shorter its total lifetime and therefore the more often it has to be replaced (IRENA, 2015). Given that battery systems for SHS range from a few hundred EUR to approximately EUR 1.000, significantly shortening the battery life can significantly increase overall system costs and increase the risk that citizens simply abandon their systems after the first battery is exhausted (Leach and Oduro 2015). In the case of cooking appliances, deep discharge is likely to occur more frequently due to the high power consumption of hot plates and other cooking appliances. Further innovation may therefore be needed to develop new battery technologies to adapt them to the specific requirements of electric cooking in SHS or mini-grids (Slade, 2015; Hoppecke, 2014).¹⁴

¹⁴ According to some analysts, lithium ion batteries might not be applicable to deliver this long-term durable performance in tropical areas (Slade, 2015). However, this might change in the coming years due to further technological developments.

Cost of Capital:

A further challenge is related to the cost of capital. Naturally, a discount rate of 5% (consistent with subsidy programs by government agencies) leads to significantly lower levelized costs than a discount rate of 20 - 30% (broadly reflecting the return expectations of typical private investors for investments with a similar risk profile in regions such as Sub-Saharan Africa). Keeping the cost of capital low for scaling-up sustainable cooking will remain critical in the years ahead.

Failure of Inability to Internalize Externalities:

Another challenge is the fact that the significant external costs of relying on traditional cooking fuels such as firewood and charcoal are rarely if ever fully internalized in the cost of cooking. Moreover, the full internalization of the external costs of cooking with firewood and charcoal arguably remains distant, and may even be unachievable in practice, for two key reasons:

- First, unlike electric lighting, or mobile phone charging, **the need to cook constitutes the basis for survival in many parts of the world;** as a result, decision-makers are unlikely, in practice, to impose the full internalization of external costs, as doing so would directly impact the poorest households hardest; in addition, doing so could risk worsening rather than improving human health and development outcomes;
- Second, **the markets for firewood and charcoal are widespread and largely under-regulated,** making it difficult in practice to introduce far-reaching taxes or surcharges to account for human and environmental externalities.

These many challenges notwithstanding, **there is room for optimism:** based on historic cost developments of solar PV and a broad range of studies showing that the past cost reductions are likely to continue (e.g. Agora, 2015) as well as recent and expected future cost reductions for battery storage (IRENA, 2015), the SHS pathway is likely to become an increasingly cost-effective solution for sustainable renewable energy cooking in rural peri-urban areas in the future. In turn, adopting electric cooking will help free up valuable time that would otherwise be spent gathering firewood that can be used for other, more valuable purposes such as going to school, looking after family, or engaging in other productive or income-generating activities.

Concluding Remarks:

Overall, the cost analysis above shows that **electric cooking based on PV-battery systems is still significantly more expensive than traditional cooking technologies such as LPG, firewood and charcoal,** as long as the health and environmental externalities remain externalized. Depending on the system size and the electricity needs for cooking appliances, the costs per household of cooking with a SHS currently range from EUR 50 to approximately EUR 150 per month depending on the specific system configuration and usage patterns (e.g. meals cooked). When compared with typical spending per household on traditional cooking fuels of between EUR 4 – 25 per month, the scale of the challenge becomes clear (World Bank 2014).




However, more conservative assumptions about total cooking related energy use, supported by continued reductions in solar and battery system costs, combined with improved cooking appliance efficiency could conceivably yield a total household cost in the range of EUR 30 per month, which is significantly closer to the range of the “willingness to pay” in many rural villages around the world, and may be considered scalable in certain regions in the near future.



4.2. Hybrid Mini-Grid Pathway

Description of the Pathway

Table 7: Actual Cooking Energy Demand and Costs for Hybrid Mini-Grids

| Actual Primary Energy Demand per Person for Electric Cooking (Range in kWh), per person per year | Approximate Levelized Electricity Generation Cost from a SHS (Equipped for Cooking Purposes, Range, in EUR/kWh) | Approximate Cost (Range), per person per year (EUR) |
|---|--|---|
| <p>1.11 – 1.43GJ (308kWh – 397kWh)</p>  | <p>EUR 0.20 – 0.90/kWh</p>  | <p>EUR 46 - 318</p>  |

Hybrid mini-grids are responsible for powering millions of rural households around the world (Schnitzer et al. 2014). They involve the hybrid use of different technologies to provide power to customers connected via a distribution network and limited to a specific geographic area that is not connected to the central power grid.¹⁵ In most cases, regardless of the primary electricity generation source used, diesel is often used as a backup or emergency source of supply. Thus, even mini-grids that are primarily “renewable” due to being powered by solar, wind, or hydropower, are often “hybrid” mini-grids in practice due to the almost universal reliance on diesel as an emergency backup, or a way to meet high demand peaks (IEA-RETD 2012).

Hybrid mini-grids can combine many different technologies in order to meet customer demand, and like all power systems, can add new generating capacity over time in order to track demand growth. Like all power systems, however, they also need to generate sufficient revenues in order to cover operating costs in order to be sustainable in the long-term.

Note that while this section focuses primarily on solar PV-diesel hybrids, other mini-grid configurations are possible

and may provide better system economics depending on the region. Other technologies that can be used effectively in a hybrid mini-grid configuration include wind power, hydropower, as well as both biomass and biogas-powered systems. However, some of these technologies tend to be more site-specific in their applications and only viable in certain locations (e.g. wind and hydropower), while others like biomass and biogas rely on the continued availability of feed stocks. The need to secure long-term and reliable feed stocks can make it challenging to operate a mini-grid system reliably and sustainably (i.e. over a 10 to 20-year period) while also meeting electricity demand growth within the village or community (Schnitzer et al. 2014). However, each of these technologies can be combined in different configurations to power mini-grid systems that could replace in part or in full the reliance on wood-based fuels for cooking.

Moreover, many residents in countries like South Africa, Nigeria, and Ghana, to name a few, already cook with electric appliances to meet at least a portion of their total cooking needs (Leach and Oduro, 2015). Furthermore, electricity is also a reliable source of energy that can be generated with a wide range of different technologies in a hybrid system, enabling mini-grids to be customized based on the best or most cost-effective local configurations. Depending on the geographic context and the overall resources available, this might involve different configurations in different markets. While the challenges of maintaining system reliability and

¹⁵ Note that hybrid in this context refers to the technologies used rather than the ownership model. For instance, mini-grids operated on the basis of a public-private partnership are sometimes referred to as “hybrid” (Schnitzer et al. 2014).

operation in a mini-grid system are often more acute due to the smaller number of households, sudden demand peaks, higher operations and maintenance costs, as well as the difficulties associated with maintaining reliability, **there is no inherent technical barrier to cooking in mini-grid systems.**

Current and Projected Costs of Cooking with Electricity from a Mini-Grid

Since each system has unique costs, and faces unique operational and maintenance related challenges over the course of its life (e.g. battery replacement, weather related damages, theft, etc.), it is difficult to definitely calculate the “true” levelized cost of generation from any mini-grid system. A further complicating factor is that the currencies with which power from mini-grid systems is often paid (particularly in developing countries) are often volatile and vulnerable to rapid inflation. Since some of the costs related to the operation of a mini-grid are necessarily borne locally and paid in local currency (such as labor costs, fuel costs for transport, replacement parts, etc.) while some are paid for in international currencies (such as module costs, battery system costs, etc.), each mini-grid is a complex agglomeration of different cost factors, making it difficult to compare the “true” costs of supply between a mini-grid in one country and one in another. As such, this report focuses primarily on cost ranges in order to provide an approximate picture of the costs of mini-grid supply.

For new solar PV mini-grid hybrids (i.e. PV mini-grid with diesel back-up), the costs of supply range from as little as EUR 0.15/kWh on the low-end (e.g. for high quality micro-hydro sites serving significant populations of several hundred or a few thousand residents that not too remote) to as much as EUR 1.80/kWh for highly remote systems serving small communities fully reliant on diesel (IEA-RETD 2012). For the purposes of this report, a more modest cost range is assumed of **EUR 0.20/kWh to EUR 0.90/kWh.**

While the decreasing costs of solar PV modules and inverters has helped improve the affordability of solar dramatically in recent years, this is only part of the story, particularly in mini-grid systems: as the cost of PV modules and associated components have come down, the share of total costs represented by solar PV modules and related components has fallen. Put differently, while further reductions in module prices (for instance) still represent a positive gain, they come to matter less and less for mini-grid economics. Conversely, other costs such site identification, load assessments, labor costs, as well as overall development costs come to matter more and more.

Challenges:

This notwithstanding, there is a number of challenges related to meeting cooking needs within a mini-grid:

Substantial Need for Storage:

in order to sustain the large cooking loads, which are often clustered in the early morning hours and the evening hours, the total size of the supply source (whether PV, wind, biomass, hydro, or otherwise), the wiring, the grid ties, as well as the battery system itself must be significantly increased beyond what they would otherwise need to be in a system powering mostly lighting and other small appliances. This is due to the large loads that cooking appliances add to the system, which includes appliances with wattages between 600 – 2300W. Due to the high peak load requirements that characterize mini-grid systems designed to accommodate electric cooking appliances, **the need for storage grows considerably.**

For such mini-grid systems, storage can represent a cost factor two to four times greater than the cost of PV modules, and can represent anywhere between 40-70% of total mini-grid capital costs (Leach and Oduro 2015; EUEI 2015).¹⁶ However, the costs of storage are widely expected to decline in the years ahead, driven by improved efficiencies, increased investment and R&D, as well as the significant economies of scale due to the rapid growth of batteries in the automotive sector (Lazard 2015; RMI 2015). This may help bring the costs down of cooking with electricity within mini-grid systems.

Co-occurrence of cooking-related electric demand:

A related problem is **the co-occurrence of cooking related electric demand**, which is comprised of dozens if not hundreds of individual appliances (depending on the size of the mini-grid) being turned on and off suddenly; this can put rapid and significant strain on the system’s operation and reliability, rapidly depleting battery systems, accelerating wear-and-tear, shortening the mini-grid’s overall operating

¹⁶ The current levelized costs of battery systems for mini-grid battery systems currently range from approximately USD \$300/kWh on the low end to USD \$1,500/kWh on the high end (Lazard 2015). The most commonly used battery types for mini-grid systems include lead-acid batteries, primarily due to their lower cost and established track record; lithium ion batteries, which are beginning to gain ground in this as well as other sectors due to their higher energy density; sodium batteries; flow batteries; and zinc-based battery systems, though the two most commonly used storage technologies in mini-grid systems are lead-acid and lithium-ion. Levelized cost of storage for lithium systems in a mini-grid configuration of between USD \$369 and \$562 (Lazard 2015). This compares with lead-acid costs of between USD \$429 and \$1046/kWh.

life, increasing maintenance and other related costs, and even forcing the system either to rely frequently on emergency back-up sources, such as diesel, or to shut down completely, interrupting service to the entire community (Schnitzer et al. 2014; EUEI, 2014). Thus, **configuring mini-grid systems to deal with massive synchronous loads (i.e. loads occurring at the approximately the same time of day) such as cooking therefore presents a considerable challenge for any mini-grid pathway to overcome.**

This is one reason why a growing number of mini-grid systems are beginning to make use of automatic feedback systems that provide real-time information to users about the state of the grid and the amount of power left in the battery bank, so that users can modify their usage patterns accordingly (Quetchenbach et al. 2012; Graillot 2015). In order to meet cooking-related needs with electricity in a mini-grid context, such feedback and so-called “load-limiting” technologies are likely to be indispensable. In a recent trial in Bhutan, the use of such technologies reduced the occurrence of brownouts in the system by 92%, which had primarily been caused by the surge in demand caused by electric cooking appliances, (Quetchenbach et al. 2012). Business models are also being developed that provide real-time price signals to end-users that fluctuate widely over the course of the day to provide direct information to end-users and encourage more efficient and system-sensitive behaviors and choices (e.g. Easy Smart Grid, 2016). Further possibilities also involve households cooking together, in order to reduce the number of appliances drawing power from the system.

Shortened Battery Life:

A further challenge that parallels one of the challenges listed above under SHS is the negative effects that high peaks in electricity demand, and deep discharging in particular, can have on battery life (see Section 4.1. above). Given that battery systems represent between 40-70% of mini-grid capital costs, decreasing the operating life of battery units used within a mini-grid system, thereby forcing them to be replaced much more frequently, can have significant impacts on the overall costs of operating the mini-grid and further push up the required tariff levels and/or subsidies required. Driving tariffs higher is likely to worsen the competitiveness of electric cooking versus other alternatives and further strengthen the incentives for users to revert back to other fuels (see below).

Reversion Risk:

A related challenge is that the high cost of cooking with electricity drives residents to revert back to traditional cooking fuels such as firewood and charcoal. For this reason, efforts to expand electric-based cooking in mini-grid systems

are likely to seem Sisyphean at first in many communities, as residents continue to opt for traditional solutions over the cleaner but costlier supply provided by electric-based options in order to save money. Alternatively, certain residents may opt to use only electricity for certain specific meals, or purposes. As highlighted previously, one cooking technology rarely if ever fully replaces another, as residents often “stack” cooking solutions upon one another as income levels rise rather than abandoning the old technologies entirely (IEA 2006). Reversion risk is likely to remain in virtually all mini-grid contexts as multiple cooking technologies continue to co-exist with one another and be preferred by different households for different purposes. Thus, equipping a village with a hybrid mini-grid designed to meet cooking loads does not necessarily mean that electric cooking will be the single or even primary mode of cooking used by local residents. As pointed out above, the displacement rate of traditional fuels for households equipped with solar systems for cooking ranges from 10-40% (World Bank 2014).

Low Income Levels/Ability to Pay:

As pointed out previously, a further financial challenge is that residents relying on electricity supply from mini-grids are typically in rural or peri-urban areas and typically have **low average income levels**. This reduces their overall willingness (or ability) to pay for energy services, particularly as many rural residents often struggle to pay for even modest monthly bills for lighting and other basic uses such as radio. Total electricity demand in a rural mini-grid context for a typical household in SSA rarely exceeds 20 - 30kWh/month (EUEI, 2014). Adding cooking loads on top of this would likely *quadruple* or more this level of electricity consumption. This is likely to push electric cooking further away from affordability and make it harder for residents to afford to continue cooking with electricity.

Concluding Remarks:

Currently, **electric cooking based on hybrid mini-grids is still more expensive than traditional cooking technologies**, provided the health and environmental externalities are not internalized. Depending on the size and total electricity demands of the village, the costs per household of cooking with a mini-grid currently range from approximately EUR 19 to EUR 130 per month depending on overall behaviors, technology choice, and usage patterns. When compared with typical spending per household on traditional cooking fuels of between EUR 4 – 25 per month, cooking with electricity is likely to remain a partial solution as residents continue to rely on traditional fuels to meet a portion of their cooking needs in order to save money (World Bank 2014).

While there are no inherent barriers to electric cooking within hybrid mini-grids, a number of important technical and financial challenges remain. On the technical side, dealing with the issue of large, co-incident loads caused by the simultaneous use of cooking appliances throughout a given village or area is likely to continue to pose a considerable challenge for years to come, one requiring both improved electronic interfaces and/or real-time pricing to encourage citizens to respond to the changing scarcity and abundance of electrical energy (stored or otherwise) available in the system.

On the financial side, efforts to introduce electric cooking are likely to be partial, at least at first: new business models, even




those coupled with significant financial and government support, are likely to find it difficult to encourage citizens, particularly those in rural and peri-urban areas, to fully substitute away from traditional fuels and technologies, due in part to the high cost of electric based options. Until the cost of mini-grid based supply can be made more affordable, and until the various social and cultural traditions adapt to embrace electric-based cooking, it is likely to prove difficult to make electric cooking widespread within mini-grid systems.

The continued availability of low- or zero-cost fuel from the surrounding environment remains one of the greatest challenges to the transition beyond fire.

4.3. Biogas Pathway

Description of the Pathway:

Table 8: Actual Cooking Energy Demand and Costs for Distributed Biogas Systems

| Actual Primary Energy Demand per Person for Electric Cooking (Range), per person per year (EUR) | Approximate Cost of each Biogas Unit | Approximate Cost (Range), per person per year (EUR) |
|--|---|---|
| <p>1.67 - 2GJ</p>  | <p>EUR 400 – 800</p>  | <p>EUR 19.94 – 52.30</p>  |

Biogas systems that rely on the breakdown of agricultural and other wastes to produce a useable gas for cooking are increasingly being deployed in rural regions around the world to meet basic household cooking needs. There are many different designs for biogas cooking systems, with some relying on brick walls or domes, and others based primarily out of plastic and other materials. The systems are typically fed with waste products from agricultural processes such as cow dung and other human wastes. When combined with sufficient moisture (i.e. water) and warmth, the systems produce a type of methane gas that can be piped directly into rural households. The most common configuration is an individual biogas system per household, although in some cases larger systems have been used that aggregate the wastes

of a few households in order to produce usable cooking gas for a collection of households. It is estimated that there were approximately 50,000 individual biogas cooking units in operation in Sub-Saharan Africa in 2014 and this number continues to grow steadily, in part due to the Africa Biogas Partnership Programme (World Bank 2014).

In addition to relying on locally available resources, biogas systems also produce valuable fertilizer for local crops in the form of slurry. This secondary product plays an important role in improving agricultural yields and increasing household incomes. It also helps reduce households' reliance on chemical fertilizers, which can also represent an important cost saving for many families.

Another important advantage of biogas systems is that they play a significant role in mitigating climate change, beyond their role in reducing deforestation. The primary feed stocks used to operate biogas systems are typically wastes from animal husbandry, which produce significant quantities of methane that would otherwise escape into the surrounding atmosphere. By capturing these and other wastes and using them in a digester to produce biogas, the total greenhouse gas emissions can be significantly reduced and put to productive use.

A final advantage to note is that based on recent field research, their ability to displace household reliance on firewood and charcoal is significantly greater than for electric-based options (66-80% versus 10-40% in the case of electric-based cooking technologies) (World Bank 2014). This is partly attributable to cost, but also to habits and overall cooking culture. This gives biogas systems a significant advantage over electric pathways due to their greater overall effectiveness at reducing unsustainable firewood and charcoal use.



Current and Projected Costs of Cooking with Distributed Biogas Systems:

The current cost range of installing a biogas system for a typical household ranges from approximately EUR 400 – 1,330 depending on the system size, production capacity, the materials used, and the overall design (World Bank 2014). The higher end of this cost range is for larger biogas systems with a productive capacity of 10-15m³ of gas per day. For the purposes of this

analysis, however, a system with a more modest daily output capacity of 6m³ is assumed, as this is the size range likely to be used by a typical individual household. The upfront cost for a household-sized biogas digester in this size range is estimated at between EUR 400 and EUR 800 per unit, plus maintenance costs, which are assumed at EUR 30/year.

In contrast to the calculations for the SHS and mini-grid technologies, where a range for the levelized cost of energy is combined with different appliance efficiency ranges, calculating the monthly or annual cost of a biogas system requires financial modeling to determine the actual daily, monthly and annual costs. In order to be more precise, it is necessary to include a few additional assumptions: due to the fact that the biogas produced by a typical biogas facility is not 100% methane, it has a lower energy density than pure methane. For the purposes of this analysis, methane is assumed to have an energy density of 38.7MJ/m³, and the methane content of biogas is assumed to be 60%, which results in an energy density for biogas (by volume) of 23.2MJ/m³.¹⁷ However, due to the greater weight of biogas compared to methane (1.15kg/m³ for biogas vs. 0.75kg/m³ for pure methane), the resulting energy density of biogas by weight is calculated at 20.2MJ/kg. It is also assumed that the biogas system produces at a capacity of 50% of its potential capacity, yielding 3m³ per day of usable gas, rather than the full 6m³.

At this level of output, a typical household biogas system would produce 69.6MJ/day of usable biogas energy per day (or just over 25GJ of biogas energy every year). Based on an efficiency for the gas stoves of between 50-60%, the total required energy per person to supply 1GJ of useful energy ranges from 1.67 – 2GJ, or 8.33GJ – 10GJ per household per year. Thus, based on the estimated energy needs per person (namely, 1GJ/person/year), a biogas system producing 3m³ per day would actually produce significantly more than the total daily household needs. The primary reason that the calculations here are based on a digester system with a maximum output of 6m³, as opposed to one with a 3m³ capacity, is that a certain minimum threshold is needed for organic wastes to produce methane in the quantities required for cooking.

With regard to the financial assumptions, the calculations assume an interest rate of 15% with no upfront payment, structured over a 10-year amortization period, and a 10-year useful life. Note that the calculations do not include the costs of the gas stove, which can range from EUR 20 – EUR 100.

Based on the assumptions outlined above, **the total monthly cooking cost per household ranges from between EUR 8,31 and EUR 21,79**, including maintenance costs. This compares favorably with the average estimated spending per household on cooking fuels of between EUR 4 – EUR 25 per month

17 See : <http://www.natural-gas.com.au/about/references.html>

(World Bank 2014), and puts biogas well within the range of being competitive with the primary traditional cooking fuels used, namely firewood and charcoal. The main challenge, as will be seen below, is the high upfront costs of the systems.

This monthly cooking cost assumes a steady operation of the system over its useful life including the use of appropriate feed stocks, continuous access to water to maintain proper moisture levels, etc. Although households do occasionally pay to obtain the necessary feed stocks, and will incur costs (in the form of time if not actual money) to gather both the feed stocks and the associated water, it is assumed here that both water and the required feed stocks are gathered from the surrounding environment and are therefore free. The same assumption is used to derive the lower end of the cost spectrum when calculating the costs of cooking with firewood.

Thus, despite having a high upfront cost per household of between EUR 400 and EUR 800, **biogas systems yield the lowest actual cooking cost per person out of all the technologies examined in this report.**

Challenges:

As with each of the other technologies examined, there are a number of challenges holding back the greater development of biogas systems for cooking.

High Upfront Cost:

At an upfront cost of between EUR 400 and EUR 800 for most household-sized systems, biogas digesters are beyond the range of affordability for most residents in developing countries, notably in the rural and remote regions. This remains the case despite the fact that on a “levelized” basis, biogas systems are fully competitive with firewood and charcoal and are much less harmful to both human health and to the environment. In order to drive the greater adoption of biogas systems, it is therefore necessary to introduce grants or subsidies, as has been done within the Africa Biogas Partnership Programme, or to encourage the development of business models that enable households to amortize the cost of the system over time.

Despite the high upfront cost, however, it is important to note one significant additional advantage of biogas systems over solar electric technologies: in contrast to solar systems, which have a displacement rate of between 10% and 40%, **the displacement rate for households equipped with biogas systems has been shown to be quite high, ranging between 66% to as high as 80%.** This means that for a wide range of reasons, biogas systems have proved to be significantly more effective at actually reducing reliance on firewood, charcoal

and other fuels (World Bank 2014). **This emerges as one of the most critical advantages of biogas systems over either of the electric pathways examined here.**

The high upfront cost of biogas systems also indicates that there is likely significant potential for further cost reductions. There are a number of innovative biogas technologies that rely more on plastic or polyethylene membranes that are beginning to enter the market, which may be cheaper to build and easier to scale-up than brick or mud-based systems. One major challenge for these cheaper models, however, is that they need to be kept away from sharp objects, as punctures in the membrane can render a system inoperable. Experience to date suggests that plastic or polyethylene biogas systems in general fail more often than other models built out of bricks or mud. Thus, before these models can become viable at a large scale and can compete on performance with brick biogas systems, further improvements are needed.

Requires Continuous Access to Feed Stocks:

The majority of biogas systems in use around the world today rely on wastes from animal husbandry such as cow dung, which are rich in nutrients and produce large quantities of methane. Due to the need for a continuous supply of feed stock, and due to the difficulties of transport, biogas systems are best suited for areas with sufficient volumes of agricultural wastes or animal wastes to maintain steady system operation. While there may be some urban and peri-urban areas where biogas systems could be viable, and could secure sufficient feed stocks, they are more likely to need to pay for the feed stocks, which can significantly increase the total operating costs. Biogas systems are therefore arguably a solution better adapted to rural and remote areas that have significant and reliable volumes of agricultural and other wastes.

Robustness:

As pointed out above, some of the newer biogas models rely on plastic or polyethylene membranes, which makes them more vulnerable to being punctured, inadvertently destroyed, or vandalized. A related challenge is the impact of animals in the surrounding environment, or of insects, which can penetrate systems and cause them to cease functioning. If systems break down too often or need costly repairs on a regular basis, this could create a perception that the technology is unreliable and deter residents from adopting them. Greater effort will be needed to ensure that the systems are reliable, that they are robust to the impacts of objects as well as the presence of animals, insects and other threats, and that they can operate successfully in a wide range of different meteorological zones and climates.

Access to Water:

As mentioned above, biogas systems need to maintain a certain level of moisture in order to operate effectively. Dry feed stocks do not produce methane in sufficient quantities to power a biogas cooking system. Thus, maintaining an appropriate environment including sufficient levels of moisture is critical to stable and continuous system operation. In some environments and at some times of the year, this may not be a problem, as water may be available from nearby streams, wells, or rivers. In other environments and at different times of the year, however, maintaining access to water will prove more difficult. Moreover, periods of drought could prove particularly problematic, as could encroaching desertification in some regions such as Burkina Faso, or Chad.

Concluding Remarks:

Biogas systems emerge as a cost-effective and viable option for meeting cooking needs, particularly in rural regions that have livestock or direct access to agricultural and other wastes. The ability of biogas systems to contribute to reducing reliance on traditional fuels such as charcoal in urban and peri-urban areas is arguably more limited, however, due to the need to secure continuous feed stocks.




A key advantage of biogas systems is that their ability to displace household reliance on firewood and charcoal is significantly greater than for electric-based options (66-80% versus 10-40% in the case of electric-based cooking technologies) (World Bank 2014). As a result, biogas systems increase the odds that initiatives and programs developed to support their scale-up will translate into greater *actual* reductions in firewood and charcoal use, including greater reductions in deforestation and in negative health effects.

At an approximate cost per household of between EUR 8 – EUR 22 per month, biogas systems compare favorably with the cost of other far more widely used fuels such as firewood and charcoal and produce far fewer harmful emissions. By concentrating dung and other wastes in a controlled way, biogas systems also simultaneously reduce the emission of methane into the environment, providing a valuable “win-win” for the global climate. **The main challenge in driving their deployment is finding ways either to reduce, or allow residents to finance, the high upfront cost.** More effort is needed to support the scale-up of biogas systems, including new business models that bring financing and know-how together to drive more rapid deployment. In addition, more research and innovation is needed to further improve the overall performance, design, and efficiency of the technology while reducing its upfront cost.

4.4. Power-to-Gas Pathway

Description of the Pathway:

Table 9: Actual Cooking Energy Demand and Costs for Power-to-Gas

| Actual Primary Energy Demand per Person for Electric Cooking (Range, in GJ), per person per year | Approximate Cost of Producing 1GJ of Energy (Range, in EUR) | Approximate Cost per person per year (Range, in EUR) |
|--|---|--|
| <p>1.67 - 2GJ</p>  | <p>EUR 29.7 – 50</p>  | <p>EUR 49 - 100</p>  |

Power-to-Gas (P2G) can involve the production of either methane or hydrogen; the focus here is on the methane pathway. P2G facilities operate first by producing hydrogen (H₂) via electrolysis, and then converting this by a secondary process into methane (CH₄) through the addition of CO₂, as shown in Figure 4 below:

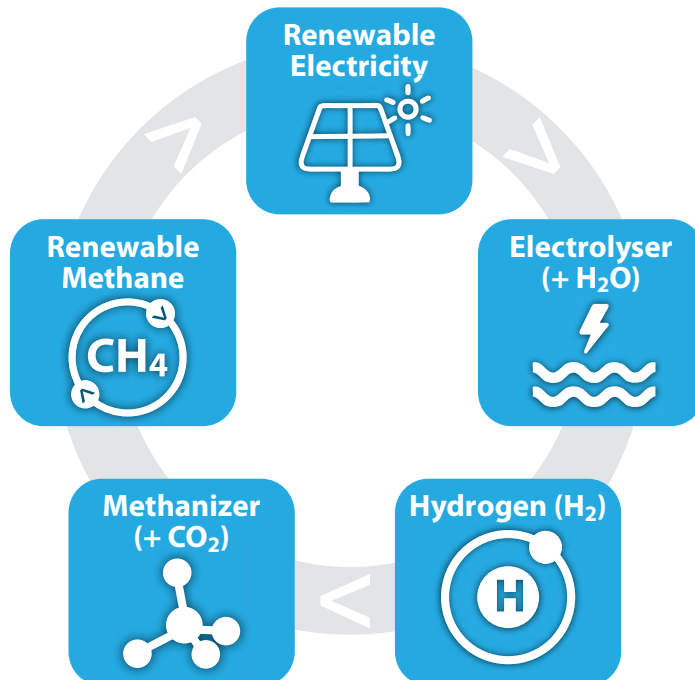


Figure 4: Schematic Overview of Methane Production via P2G

In order to produce methane, a source of CO₂ is required as a feedstock, which can be obtained from a range of different sources (BMVI 2014):

- **Fully sustainable:** CO₂ from biological sources such as from biogas facilities, wood combustion. Alternatively, CO₂ can be harvested directly from the ambient air.
- **Partly sustainable:** CO₂ from industrial processes such as cement production
- **Non-sustainable:** CO₂ from fossil fuel-based industrial processes such as coal-fired power plants or others.

Each of these different sources of CO₂ has different advantages and disadvantages, and exhibit different costs, which is likely to impact which options are viable where. At the moment, capturing CO₂ from the ambient air remains more expensive than the other options, but this could change as systems scale up and processes for concentrating CO₂ become more efficient. Ultimately, different feed stocks are likely to be used in different jurisdictions depending on the

local context, and different feed stocks may even be used over the course of an individual project's life.

Another common concern around P2G technologies is efficiency. However, recent analysis suggests that the overall efficiency of producing methane from electricity is comparatively quite high, ranging from 55 – 80% when both the electrolysis and methanation processes are taken into account (Ahern et al. 2015). This overall conversion efficiency is likely to play an important role in enabling the scale-up of P2G in the years ahead, potentially for both cooking and transport related purposes (BMVI 2014; Ahern et al. 2015).

Plants could be located on the periphery of large urban areas, and could be designed to draw on the existing distribution channels for LPG, effectively introducing a renewable alternative to fossil-fuel based LPG. In the early stages, the P2G would likely need to be subsidized in order to ensure it remains cost-competitive with alternatives (including traditional LPG in markets that have access to it), though these subsidies could be ramped down over time as the total system costs decline and the overall cost of production declines due to economies of scale.

In this way, the introduction and scale-up of large-scale P2G facilities powered by renewable energy sources such as solar in markets with great solar resources, or geothermal in markets with abundant geothermal resources such as Kenya or Ethiopia, or even by hydropower in markets with abundant hydro resources such as Zambia, or the Democratic Republic of the Congo (DRC) could theoretically provide a viable pathway for making the majority of the cooking fuels used in any market in Sub-Saharan Africa come from renewable sources.

Current and Projected Costs of Cooking with Power-to-Gas

Single gas burners are available in Sub-Saharan Africa for EUR 15-25 while double burner stoves are available for between EUR 18-40. In addition, customers typically have to pay a one-time fee for the LPG cylinders, which cost between EUR 25-30 (Leach and Oduro 2015). This results in a total “start-up” cost of EUR 40 to EUR 65 per household. In addition to this, the household has to purchase the fuel itself, which ranges between EUR 1,50/kg and EUR 2,50/kg, and commonly comes in 15kg cylinders.

The 15kg cylinder provides on average 5 weeks of cooking for the average household (Leach and Oduro 2015). At an average price for LPG across SSA of roughly EUR 2 per kg, the cost of filling the cylinder would be approximately EUR 30, which translates into a daily cooking cost of roughly EUR 1 per household per day (Leach and Oduro 2015). While this remains more expensive than firewood, charcoal biogas, and other models based on wood or waste pellets, it remains within the range of affordability.

With regard to the P2G systems themselves, the current cost picture is evolving rapidly but preliminary figures suggest a total capital cost for a facility of 10MW would cost between EUR 30-31 Million, with the potential to decline in half by 2050 (ENEA 2016). A current system that has recently been built in Hamburg with an electrolyser capacity of 1MW cost EUR 13,5 Million (E.ON 2014), while estimates for projects in the UK show similar numbers (ITM Power 2014). With regard to the total levelized costs of renewable gas production, the most recent estimates conducted suggest a cost range of between EUR 0.107 – 0.18/kWh produced, which translates into a cost of EUR 29.7 – EUR 50 per GJ (Benjaminsson et. Al. 2015). **On this basis, the costs for an individual household consuming 8.33 and 10GJ of cooking energy per year would range from EUR 247 – EUR 500, or between 0.68 and 1.37 EUR per day.** Thus, producing a GJ of available thermal energy in the form of P2G would currently be affordable for end-users in a range of different markets across SSA as well as across much of Asia, if the right infrastructure were in place. Under attractive conditions, including with targeted government support, the cost could be

made more affordable still, particularly in regions that do not already have access to LPG.

As pointed out above, one of the key advantages of a gas-based pathway from the perspective of end-users is that the upfront cost for end-users is relatively inexpensive when compared to the upfront cost of a SHS. Under a targeted initiative to scale up P2G, the upfront cost of both the cylinders and the gas burners could be bundled into a pay-as-you-go contract similar to those used to scale-up SHS in many countries around the world, making the cost even more affordable.

A further characteristic of the P2G pathway is that it represents a fundamentally different approach to addressing the challenge of sustainable cooking: First, it involves a fundamentally different kind of capital investment, involving one large centralized investment rather than thousands of small investments. This may make it interesting for certain kinds of lenders, international donors, and may even be preferred by certain governments as well as by regulators. It may also be perceived as lower risk from a transactional standpoint, as there are fewer factors that can cause the overall business model to fail, unlike in hybrid mini-grids where sustainable, long-term operation remains the exception, rather than the rule (Schnitzer et al 2015; REN21/EUEI 2014).

A further advantage is that the P2G systems could be powered with a wide range of different electricity sources, including power from the centralized power grid. It could be adapted to the local country's best available resource, whether geothermal in markets like Kenya, hydro in Zambia, or solar PV in Burkina Faso.

Challenges:

As with the other pathways examined, there is a number of challenges facing the P2G pathway:

High Upfront Cost

One of the main challenges for achieving a sustainable, renewably-based power-to-gas system is the high upfront cost of the electrolyser and the associated power plant required to supply it. Due to the relatively high cost (approximately EUR 700/kW_{el}), it is economically desirable to operate the facilities at a high capacity factor (e.g. over 80%), which may require a mix of different renewable power projects or the combined use of power from the grid, representing a combination of both renewable and conventional forms of generation (BMVI 2014). The high upfront cost may also make it difficult to find investors willing to put that much capital at risk, at least in the early stages, particularly if uncertainty remains over the future availability and taxation/subsidization of other fuels such as LPG.

Securing a Reliable Source of CO₂:

Another challenge for the P2G pathway is finding a sustainable and cost-effective source of CO₂ to fuel the methanation process. Further progress is likely needed in this area, and different solutions will need to be explored in different market contexts based on the different sources of CO₂ available.

Fewer Co-Benefits:

Also, the P2G pathway does not provide the same co-benefits as the SHS and mini-grid pathways, which also provide electrification to the communities targeted. Given the multiplicity of benefits that improved access to electricity can bring, any strategy to promote energy access that focuses solely on cooking needs is incomplete. The question for policymakers becomes whether it is more cost-effective to meet basic electricity needs with a small and appropriately dimensioned SHS or mini-grid, and meeting cooking needs with an alternative cooking technology that does not rely on electricity such as P2G, LPG, pellets or or biogas systems. Further analysis is needed on the relative costs and merits of different cooking configurations to clarify these and other issues.

Competition with LPG:

A further challenge is that any renewably generated gas that enters a given market is likely to compete directly with existing LPG fuel, which is likely (at least in the early stages) to be more affordable. This is compounded in many countries by the existence of direct and indirect subsidies offered for LPG. Any effort to scale up renewable gas via P2G will therefore need to be coupled with a reexamination of the existing subsidy environment, or will need to be targeted at regions that do not yet have access to LPG. In the early stages, governments may even want to directly support renewable gas production in their country by providing targeted subsidies to bridge the cost gap and accelerate its adoption. This may be best accomplished in the context of broader fossil fuel subsidy reform, particularly as the majority of fossil fuel subsidies awarded in most countries continue to benefit middle and upper-income families most.

Restructuring fossil-fuel subsidies and re-allocating them to support the transition to sustainable cooking could bring significant economic, environmental, and social gains, while helping ensure that subsidies are allocated to those who need them most.

TEXT BOX 2: BRAZIL SUCCESSFULLY SWITCHED SUBSIDIES FROM FOSSIL FUELS TO LPG

In May 2001, Brazil began to ramp up the subsidies for LPG, specifically targeting low-income households: only families with an average annual income of less than half of the minimum wage were able to qualify, which primarily supported fuel switching away from wood and charcoal in rural and remote communities. At the same time, the government reduced subsidies on other fossil fuels and allowed their prices to reflect market prices. By the end of 2002, the cost of the LPG support program was half that of the previous subsidies, and yielded a wide range of environmental and health benefits across the country. By 2006, 98% of Brazilian households had access to LPG, due in part to the targeted support provided under the program (IEA 2006). In such a context, the main advantage of switching to P2G would be that the fuel itself could be renewable, and therefore provide a more long-term, sustainable solution.

Carbon Emissions:

One common concern with P2G is that despite requiring CO₂ to produce the gas, it also emits CO₂ when burned. While P2G is not entirely carbon neutral (as the gas still has to be burned) the carbon emissions produced would be a fraction of those produced from the use of conventional fuels like wood or charcoal, and likely within the range of those from pellet systems. A major analysis conducted for the transport sector concluded that the total emissions from P2G amounted to perhaps 10-15% of the equivalent emissions of a diesel or gasoline powered vehicle, and that the carbon balance remained positive up to an average CO₂ content in the power mix of roughly 160-170g CO₂ equivalent/kWh (BMVI 2014), which is approximately the average CO₂ content of the power mix of Austria (EEA 2010). When compared to wood or charcoal based consumption, and factoring in the CO₂ savings from reduced deforestation, soil erosion, etc., the net benefits of switching to P2G are still likely to be considerable.

Transport Costs:

A further challenge is that **the economics of distributing gas cylinders worsen as transport costs increase**, a factor that may make it inappropriate for extremely rural or remote regions. Thus, for regions with very low population densities (e.g. fewer than 2-3 inhabitants per km²), the cylinders would face significant transport cost premiums, potentially making them uncompetitive with other locally available fuel sources. Minimizing transport costs would likely require a

relatively distributed approach, with dozens if not hundreds of individual P2G facilities in each country serving different regions. The high transport costs may make P2G unviable in certain regions, particularly where road infrastructure is poor.

Concluding Remarks:

Like all pathways examined here, P2G is likely to require significant public or donor-based funding to cover the high upfront costs and to ensure that the prices paid by end-users

remain affordable. This could also be partnered with targeted subsidies for low-income or rural residents, in order to further bridge the cost gap, potentially by reforming existing fossil fuel subsidies, which all too often favor middle and high-income residents, and restructuring them to directly benefit low income, rural residents (see IISD 2013, IEA 2011).

However, if the renewable gas could be made available at a cost that is affordable to both rural and urban residents, it could in principle provide a durable, long-term solution to the challenge of achieving sustainable cooking.



5. SYNTHESIS AND KEY FINDINGS

In order to transition to truly sustainable cooking, it is necessary to think beyond improved cook stoves and beyond traditional fuels such as firewood and charcoal. The current demographic trends in most regions of the world where reliance on biomass-based fuels is high make continued reliance on biomass-based fuels unsustainable in the medium to long-term.

In addition to helping reduce unsustainable rates of deforestation and biomass harvesting, the cooking options presented here can contribute significantly to reducing greenhouse gas emissions in many regions of the world. Indeed, **reducing emissions from the cooking sector must be at the heart of efforts to tackle global climate change.** It can also play an important role in reducing the millions of pre-mature deaths caused by indoor air pollution linked to traditional cooking technologies. Concerted efforts to help rural and peri-urban residents transition away from traditional biomass can therefore contribute to a significantly higher quality of life for millions of citizens around the world.

Furthermore, by freeing up the time of young children and mothers from the burden of gathering and transporting solid fuels like wood or charcoal, **transitioning to sustainable cooking can also help promote future economic prosperity, contribute to reducing gender inequality, all while supporting improved literacy and numeracy in countries around the world.**

Another key finding of this report is that **focusing on cost alone is insufficient:** policymakers, government officials, and donors should factor in the very real negative externalities (both near-term and long-term) of wood and charcoal use.

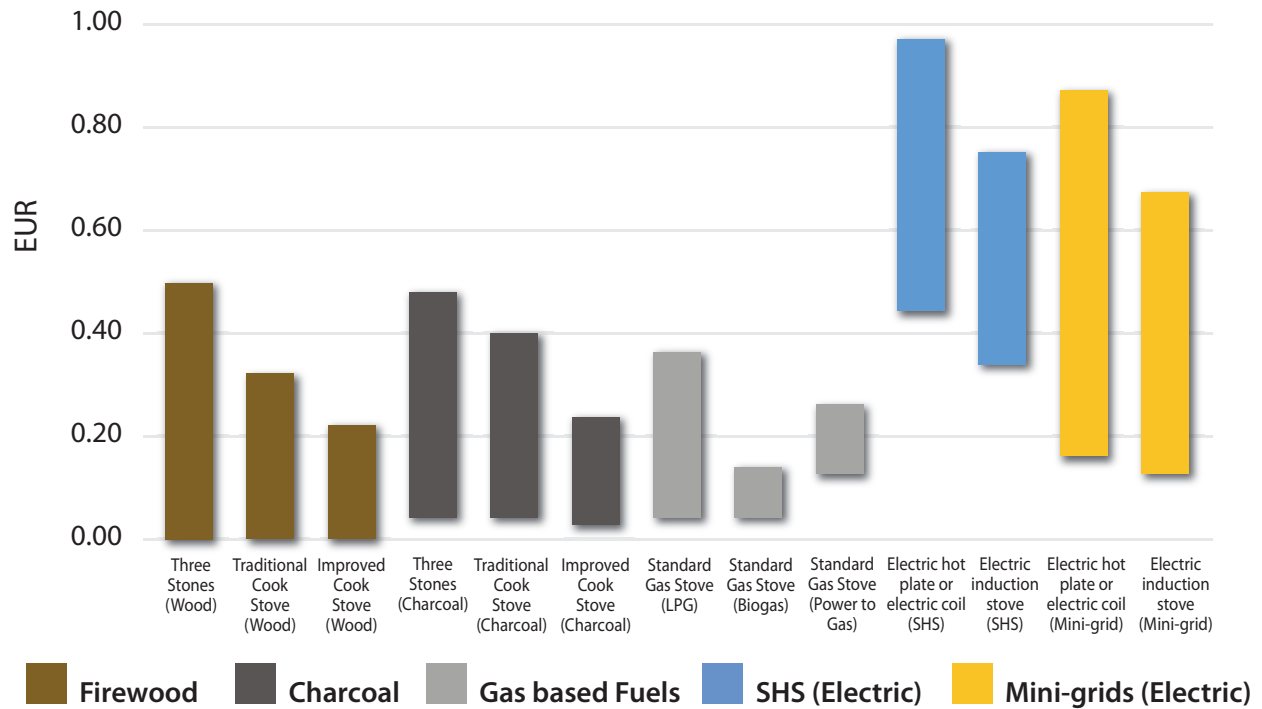
Doing so would bring far greater attention to the issue of sustainable cooking and demonstrate that even though large-scale interventions in the cooking sector may seem expensive at first glance, the total savings through reduced human and ecological impacts make these investments increasingly urgent, if not necessary. **Grasping the sheer magnitude of the negative externalities associated with traditional cooking technologies can help in building the political will required and mobilizing the investments needed.**

Based on the cost data gathered and presented above, it is possible to provide a comparative analysis of the different costs for each technology. For achieving sustainable cooking, the benchmark used is the cost of producing a thermal unit of energy with a given technological pathway, in this case, a Gigajoule (GJ). This benchmarking is considered necessary in order to objectively compare the different costs of different cooking pathways. At the core of this calculation is that **the estimated useful energy used for cooking per person is 1GJ per year**, based on Sanga and Januzzi 2005, and supported more recently by Demierre et al. 2014.

Drawing on this number, the figure below provides a summary of current cost ranges, in EUR/GJ, of the various cooking options considered within the report. Note that costs vary largely within each technology category due to the wide range of cost factors, including total system costs, appliance efficiency, user behavior, etc. Note also that the calculation (for instance in the case of electric options) is based on accepted ranges of costs based on the approximate levelized cost of energy, or LCOE, of different options, rather than a component-based approach that gathers and analyses the costs of each individual cost factor (e.g. panels, wiring, etc.).



Figure 5: Cost Ranges of Various Cooking Technologies (Per Person, Per Day, in EUR), 2016



Sources: Authors' elaboration, based partly on Leach and Oduro, 2015; Goodwin et al. 2014; GACC 2015; Adkins 2010; Smith et al. 2013; FNR 2016.

Assumptions: The high end of the cost range for all technologies assumes that 100% of cooking needs are met with this technology or fuel source, under the least efficient/most expensive conditions.

Wood: the low end of the range assumes that the cost of gathering wood is zero; the high end of the cost range represents a firewood cost of EUR 0.15/kg. It is important to note, however, that the upper end of the cost range shown here would rarely ever be attained, as most households gather a portion of their own firewood, and few pay a rate as high as EUR 0.15/kg at all times. The energy conversion rate for wood is assumed to be EUR 60.6kg/GJ, or 16.5MJ/kg. **Charcoal:** the cost estimates for charcoal ranges from a low of EUR 0.10/kg and a high of EUR 0.50/kg. The energy conversion rate for charcoal is assumed to be 35.1kg/GJ, or 28.5MJ/kg. **Liquefied Petroleum Gas (LPG):** the cost estimates for LPG ranges from EUR 8.7/GJ to EUR 67.5/GJ. The energy conversion rate of LPG is assumed to be 21.8kg/GJ, or 45.9MJ/kg. **Biogas:** The cost range for a household-sized biogas digester with a production capacity of 6m³ of biogas per day is estimated to range between EUR 400 and 800 per digester unit, plus maintenance costs of EUR 30/year. The methane content of the biogas is assumed to be 60%, which results in an energy density of 23.2MJ/m³. At an average daily production rate of 3m³ per day (50% of its maximum output), this provides a total energy output of 69.6MJ per day. Due to

the greater weight of biogas compared to methane (1.15kg/m³ for biogas vs. 0.75kg/m³ for pure methane), the resulting energy density of biogas is calculated at 20.2MJ/kg. The biogas system operating life is estimated at 10 years. The modeling assumes an interest rate of 15% with no upfront payment, structured over a 10-year amortization period. This results in a monthly cost of between EUR 8,31 and EUR 21,79 (including maintenance costs), and assumes a steady operation of the system over its useful life including the use of appropriate feed stocks, continuous access to water to maintain proper system functioning, etc. Although households do occasionally pay to obtain the necessary feed stocks, it is assumed here that feed stocks as well as water are gathered from the surrounding environment and are therefore free. Note that based on the estimated energy needs per person (1GJ/person/year), a biogas system producing 3m³ per day would actually produce significantly more than the total daily household needs. **Power to Gas (P2G):** the cost estimates for P2G range from 29.2EUR/GJ to roughly 50EUR/GJ. The energy conversion rate of methane produced via P2G is assumed to be 21.8kg/GJ, or 45.9MJ/kg. **Solar Home Systems (SHS):** The estimated levelized generation cost range for SHS ranges from EUR 0.40 to 0.90/kWh, depending on system size, configuration, component type, and soft costs. The energy conversion rate is 277.7kWh per GJ, or 3.6MJ/kWh. **Mini-grids:** the estimated levelized generation cost range for mini-grids ranges from EUR 0.20 to 0.90/kWh, depending on the system size, configuration, as well as the associated operation and maintenance costs. The energy conversion rate is 277.7kWh per GJ, or 3.6MJ/kWh.

Table 10: Key Assumptions

| Energy Source | Cooking Technology Used | Conversion efficiency of cooking appliance (range) | Actual primary energy demand per person per year (in GJ) | Cost range per person per year (in EUR) | Cost per person per day (in EUR) | Actual primary energy demand per household per year (in GJ assuming 5 people per household) | Cost range per household per year (5 people per household in EUR) |
|-------------------------|-------------------------------------|--|--|---|----------------------------------|---|---|
| Wood/Dung | Three Stones | 5-20% | 5 - 20GJ | 0 - 182 | 0 - 0.50 | 25 - 100GJ | 0 - 913 |
| | Traditional Cook Stove | 10-25% | 4 - 10GJ | 0 - 120 | 0 - 0.33 | 20 - 50 GJ | 0 - 600 |
| | Improved Cook Stove | 15-40% | 2.5 - 6.66GJ | 0 - 80 | 0 - 0.22 | 12.5 - 33.3GJ | 0 - 400 |
| Charcoal | Three Stones | 10-25% | 4 - 10GJ | 14.04 - 175.50 | 0.04 - 0.48 | 20 - 50GJ | 70.2 - 877.50 |
| | Traditional Cook Stove | 12-30% | 3.33 - 8.33GJ | 11.69 - 146.19 | 0.03 - 0.40 | 16.65 - 41.67GJ | 58.45 - 730.95 |
| | Improved Cook Stove | 20-50% | 2 - 5GJ | 7.02 - 87.75 | 0.019 - 0.24 | 12.5 - 25GJ | 35.1 - 438.75 |
| LPG or natural gas | Standard gas stove | 50 - 60% | 1.67 - 2GJ | 14.53 - 135 | 0.04 - 0.37 | 8.33 - 10GJ | 72.65 - 675.00 |
| Biogas | Standard gas stove | 50-60% | 1.67-2GJ | 19.94 - 52.30 | 0.055 - 0.15 | 8.33 - 10GJ | 99.70 - 261.48 |
| Power to gas | Standard gas stove | 50-60% | 1.67-2GJ | 49.6 - 100 | 0.14 - 0.27 | 8.33 - 10GJ | 247 - 500 |
| Electricity (SHS) | Electric hot plate or electric coil | 70% | 1.43GJ | 158.88 - 357.490.44 | 0.98 | 7.14GJ | 798.40 - 1787.45 |
| | Electric induction stove | 90% | 1.11GJ | 123.33 - 277.490.34 | 0.76 | 5.56GJ | 616.65 - 1387.45 |
| Electricity (Mini-grid) | Electric hot plate or electric coil | 70% | 1.43GJ | 59.63 - 317.75 | 0.16 - 0.87 | 7.14GJ | 298.15 - 1588.75 |
| | Electric induction stove | 90% | 1.11GJ | 46.29 - 246.64 | 0.13 - 0.68 | 5.56GJ | 231.45 - 1233.20 |

The findings for the three different pathways examined here can be summarized as follows:

Solar Home Systems: Solar home systems (SHS) provide one potential pathway to support the transition to sustainable cooking. As the costs of SHS components continue to decline, notably solar panels and batteries, SHS may become a viable option for households in rural and peri-urban areas. However, due to the significantly larger capacity (i.e. wattage) and electricity demand requirements than a traditional SHS configured to provide lighting and mobile phone charging, this translates into a need for more solar panels and larger battery systems, which significantly increases the total system costs. This report estimates that based on currently available technologies and current cost ranges, **the cost of cooking with a SHS ranges from EUR 0.34 – EUR 0.98 per person per day, or from EUR 1.70 to EUR 4.90 per household per day for a five-person home**, depending on the specific technologies used, the size of the household, the efficiency of the appliances, etc.

Due to the comparatively higher cost compared to either wood or charcoal, the roll-out of SHS that are dimensioned to meet cooking needs should, in the early stages, ideally be targeted

at regions or households with higher per capita income, where the higher monthly payments are more affordable and may be more readily seen as a worthwhile trade-off when compared to gathering fire-wood or purchasing charcoal. This can provide valuable lessons and can help further drive down costs for other households in the process.

Like with each of the pathways explored in this report, the comparatively high upfront costs combined with the continued availability of near zero-cost alternatives such as gathering wood (excluding the opportunity costs as well as the significant health impacts and other externalities) make it necessary that governments provide far greater and more targeted financial support to drive the transition to sustainable cooking. Providing direct grants or targeted co-financing can help support the roll-out of such systems, and can help buy-down the total system costs, thereby helping to make them affordable to a wider spectrum of the population.

Hybrid Mini-grids: Hybrid mini-grids is a category that includes a wide range of different generation technologies that can be combined together to meet the needs of a given village or community, typically in rural or peri-urban regions. This

report focuses on hybrid mini-grids powered by renewable energy (RE) sources. Meeting cooking needs with hybrid mini-grids is found to be more cost-effective than with SHS, **at an estimated cost range of EUR 0.13 – 0.87 per person per day**, or EUR 0.65 to EUR 4.35 per household per day, depending on the technologies used, the size of the village, the efficiency of the appliances used, etc. However, adding dozens if not hundreds of high-wattage cooking appliances within a mini-grid, with wattages ranging from 600W to 2300W for single and double-burner hotplates or electric coils, generates a range of additional challenges.

Since most cooking is done at the same times of day (namely in the early morning and early evening hours), this can create massive peaks in electric demand and in total peak capacity, which can negatively impact mini-grid functioning, reduce reliability, increase operations and maintenance costs, and even induce black-outs (Graillot, 2012). As a result of these and other related challenges, this report finds that introducing and scaling up electric cooking appliances within a mini-grid context is likely to require more advanced user interfaces and/or metering technologies to provide signals directly to customers about the state of the system, and its ability to accommodate more cooking-related loads at any given moment. In the absence of load-limiting mechanisms, the risks of frequent unreliability caused by the addition of large cooking loads in small mini-grid systems is likely to further increase the risks of mini-grids tipping into a vicious cycle (see Schnitzer et al. 2014), with decreasing customer satisfaction, low cost recovery, significant unmet demand, resulting in a gradual transition back to previous cooking technologies.

Thus, finding ways to ensure that renewable energy-powered mini-grids can be both reliable and cost-effective is critical to making mini-grids a viable and scalable option to achieve sustainable cooking. The roll-out of mini-grids configured to meet cooking needs may therefore need to be targeted, at least in the early stages, at regions with relatively higher per capita income, such as peri-urban areas, as well as in countries with comparatively higher average income levels. Governments and donors seeking to support mini-grids equipped to meet cooking needs could assist by providing grants or direct co-financing, as is often done within rural electrification strategies, with subsidies awarded on a per-person or per-household basis. Such targeted co-financing can bring down the total system costs and help make sustainable cooking solutions more affordable. A related approach would be for governments and donors to finance demonstration projects that can help prove the overall technical viability of sustainable mini-grid based cooking solutions while identifying any further issues and challenges that need to be overcome.

Like with the SHS pathway, the comparatively high upfront costs and ongoing operational costs of mini-grids, combined with the continued availability of wood and charcoal make it necessary that governments and donors provide much greater financial support to drive the transition to sustainable cooking. These and other potential solutions are explored in greater detail in Section 6 of the report.

Distributed Biogas:

The cost range of a biogas system large enough to meet a household's energy needs is estimated at between EUR 400 and EUR 800, while the **the total cooking cost per person per day (for a household of 5) ranges from between EUR 0.055 and EUR 0.15**, including maintenance costs. This translates into a daily cost per household of EUR 0.275 and EUR 0.75. Although the upfront cost of a biogas system is considerable and well above the ability of most households to afford in one payment, the monthly cost range (of EUR 8.31 – 21.79) compares favorably with the average estimated spending per household on cooking fuels, which is estimated to be between EUR 4 – EUR 25 per month (World Bank 2014). Thus, despite having a high upfront cost, **biogas systems are broadly competitive with the most widely used traditional cooking fuels, namely firewood and charcoal** (World Bank 2014).

The main challenge, as highlighted above, is to find ways to make the systems available to a wider spectrum of the population, particularly in rural and remote regions, by enabling the high upfront costs to be amortized over time.

While biogas systems do not yield the same level of co-benefits as the electric-based options examined here, their greater cost-competitiveness makes them an attractive, if not necessary, part of the toolkit to help the transition off traditional fuels. An important factor, however, remains access to reliable feed stocks, as well as to water, both of which must be continuously available to ensure continuous methane production. This is one reason why biogas systems are most often deployed in regions where livestock is kept, as livestock provide a reliable source of raw materials.

A notable advantage of biogas systems over the electric cooking pathways examined here is that in contrast to solar systems, which have a displacement rate of between 10% and 40%, **the displacement rate for households equipped with biogas systems has been shown to be remarkably high, ranging between 66% and 80%**. This means that in practical terms, biogas systems have proved to be more effective at actually reducing reliance on firewood, charcoal and other fuels than electric pathways (World Bank 2014).

Based on these and other advantages, and given that there are only an estimated 50,000 biogas systems in all of SSA at the moment (World Bank 2014), more effort is needed to support the scale-up of biogas, including new business models that make it affordable and assist in their construction, and in the transfer of knowledge required to build and maintain them.

Power-to-Gas: Power-to-gas (P2G) involves using electricity to produce synthetic methane. While in Europe and North America P2G is often thought of as an alternative to conventional natural gas, or as a form of storage for excess renewable energy production, in other parts of the world P2G could be used to generate a renewably produced fuel that could directly meet residents cooking needs, much like liquefied petroleum gas (LPG) does in many markets across Africa, Asia, and Latin America today. And while P2G may not be competitive with conventional natural gas delivered by pipeline, the preliminary results of this report found that it is broadly cost-competitive with current LPG prices and that it could provide a more cost-effective option to meet cooking needs than either mini-grid based electricity supply or SHS, with **a price range of EUR 0.14 – EUR 0.27 per person per day**, or roughly EUR 0.70 to EUR 1.35 per household per day, depending on the technologies used, the size of the system, the cost of key inputs such as electricity costs, the source of carbon used, etc. The delivery model used for P2G would likely follow that of the LPG industry, as P2G could be centrally produced with renewable energy sources such as solar PV, wind power, or geothermal, and could be distributed in individual cylinders to residents living in urban, peri-urban, and even rural regions.

A further factor supporting P2G is that residents around the world are typically already familiar with gas stoves of the kind used for kerosene or LPG: the pathway therefore poses no significant cultural or behavioral challenges, as it can be readily integrated into existing cooking habits and behaviors. Although the actual business model for generating renewably-produced P2G would need to be developed and refined, this analysis finds that there is no significant technical or cost barrier to the wider use of P2G, particularly in regions where good renewable energy resources are available. In fact, both P2G and the biogas pathway (the latter of which is only considered briefly) appear, under current market circumstances, to be more cost-effective alternatives to achieve sustainable cooking than either of the electric-based pathways considered here. However, it must be noted that P2G, like LPG, still releases CO₂ into the atmosphere, and as such, would have a higher carbon footprint than either the mini-grid or SHS pathways described. This is one clear area where further analysis is needed to accurately quantify the net carbon balance of transitioning to cooking with renewably-generated P2G.

Furthermore, the P2G pathway does not provide the same co-benefits as the SHS and mini-grid pathways, which simultaneously provide electrification to the communities targeted. Given the multiplicity of benefits that improved access to electricity can bring, focusing solely on the P2G pathway for cooking without also improving access to electricity would fail to promote complete and balanced energy access, as intended by many leading initiatives such as the SE4ALL initiative and the United Nations' Sustainable Development Goals (SDGs). **The question then becomes whether it would be more cost-effective to provide electricity in smaller-scale systems (either SHS or mini-grids) that are equipped to meet basic electricity needs, and meeting cooking needs with alternative, non-electric pathways such as P2G, LPG, pellets, or biogas systems.** This uncertainty underscores the need for far greater investment in this area, including targeted pilot projects designed to evaluate these various factors.

Finally, it is important to note that the economics of distributing gas cylinders worsen as transport costs increase, which would therefore likely favor a somewhat distributed approach with dozens if not hundreds of individual P2G facilities in each country serving different regions. Like all pathways examined here, P2G is likely to require significant public or donor-based funding to cover the high upfront costs and to ensure that the prices paid by end-users remain affordable. This could also be partnered with targeted subsidies for low-income or rural residents, in order to further bridge the cost gap, and with broader political efforts to reform existing fossil fuel subsidies, which all too often favor middle and high-income residents (see IISD 2013, IEA 2011).

The high upfront cost of switching to alternatives is perhaps the most widely cited challenge to the transition to cleaner cooking solutions (IFC 2012; World Bank 2011; World Bank 2014; Leach and Oduro, 2015); overcoming this challenge is therefore critical. As the examples of Tanzania and Uganda cited earlier show, the upfront cost of adopting new technologies is decisive: the willingness to invest in more expensive stoves dropped precipitously when the price rose from USD \$10 per unit to \$17.5 per unit (Adkins et al. 2010). **Interventions in the cooking sector must therefore be designed to recognize the key role of cultural and behavioral factors in accelerating or slowing down the rate of adoption of cleaner cooking technologies.** Ultimately, efforts to promote more sustainable cooking technologies will not work unless accompanied by corresponding behavior change in the targeted populations (World Bank 2014; Goodwin et al. 2014; Atteridge et al. 2013).

Thus, whatever business model is used to help drive the scale-up of a new technology, be it SHS, renewable mini-grids, or P2G, it has to make the new cooking pathway affordable from the outset, which is likely to involve amortizing the cost of the technology into small, affordable payments, such as in pay-as-you-go structures. And in the early years, **scaling-up sustainable cooking is going to require significant and sustained financial resources, including from governments, donors, and other international agencies active in the sector.**

It is commonly argued that the lack of finance is a critical barrier to the uptake of new technologies in regions like Sub-Saharan Africa (IEA 2014). While the scale of the financing need is undoubtedly significant, such large investments are increasingly drawing the attention of traditional investors such as pension funds and sovereign wealth funds, which are increasingly eager to invest in projects that contribute to

long-term sustainability. With the right level of both public and political support, it is undoubtedly possible to mobilize billions to tackle the challenge of sustainable cooking – what is needed is concerted policy attention, combined with dedicated long-term financial support, and critically, the political will needed to make sustainable cooking a reality.

Against the backdrop of broader global objectives such as the recent UN Sustainable Development Goals as well as the recent COP21 Agreement reached in Paris in December 2015, the challenge to transition to alternative modes of cooking may not be as insurmountable as it once seemed.¹⁸

18 UNEP (2015). “The Financial System We Need: Aligning the Financial System with Sustainable Development,” Available at: http://apps.unep.org/publications/index.php?option=com_publication&task=download&file=011830_en ; UNFCCC 2015, Available at: <https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>



6. BEYOND FIRE: 5 STEPS TO ACHIEVE SUSTAINABLE COOKING

This report closes by outlining a list of five (5) steps to accelerate the transition to sustainable cooking:

1. **Governments need to set clear goals to transition away from firewood and charcoal.** The current energy strategies being developed throughout most of Africa and Asia are not doing enough to drive a meaningful transition toward sustainable cooking solutions. Current strategies largely focus on improved cook stoves and the build-out of LPG infrastructure, failing to recognize the tremendous potential of alternative cooking solutions such as renewable electricity, biogas, and P2G. By focusing largely on improved cook stoves, many in the international community are choosing to ignore the underlying demographic trends that are likely to make any long-term reliance on wood-based fuels for cooking unsustainable in the long-run. In order to make meaningful progress toward sustainable cooking, governments will need to commit to far more ambitious goals, including clear strategies and clear financing mechanisms to implement them, and donor organizations will need to think beyond the current focus on improved cook stoves.
2. **Governments should undertake root-and-branch reform of fossil fuel subsidies, which often benefit middle and upper-income residents, and re-allocate them to support a rapid scale-up in sustainable cooking technologies.** In contrast to existing fossil fuel subsidies around the world, which tend primarily to benefit citizens with medium to high income levels, targeted support for sustainable cooking technologies tend, by default, to support lower income households. Re-allocating fossil fuel subsidies to accelerate the transition toward sustainable cooking would bring massive and lasting benefits to sustainable development, and would contribute significantly to re-balancing the major inequities that continue to persist between urban and rural regions. Reforming fossil fuel subsidies and re-allocating the proceeds to support sustainable cooking is perhaps one of the single most impactful steps that governments around the world can take to accelerate the transition.
3. **Governments and donors around the world need to fund a greater range of projects to demonstrate the viability of sustainable cooking solutions, including electric, biogas, and P2G pathways, as well as to support the scale-up of new business models in the cooking sector.** These kinds of projects can be extremely valuable in order to gather cost and performance data, analyze behavioral and other challenges, while driving further technological innovation and cost reduction. Moreover, strategically supporting the emergence of new business models can help give rise to replicable, scalable projects at various points of the cooking value-chain. Skepticism of alternative cooking solutions remains high, not least among end-users: one of the best ways to overcome this is first to demonstrate their viability, and then to help drive technological improvement and cost reduction by expanding the market, and improving the overall mechanisms of delivery.
4. **Governments, in partnership with international donors, should introduce clear policies and incentives to reduce upfront costs.** This can involve targeted grants to encourage adoption and foster economies of scale; it can also involve other policies to help bridge the cost gap, such as “feebates” (e.g. additional fees on certain items such as air conditioning units or automobiles that are allocated to support rebates on other technologies, in this case, sustainable cooking technologies); a further approach might involve the targeted use of tax or duty exemptions, such as those frequently offered on solar PV components. These measures may be combined with other legal and regulatory measures, such as restrictions on charcoal use and distribution, or better monitoring and delivery mechanisms to ensure that the benefits reach end-users.

- 5. International climate finance should be mobilized to play a far greater and more direct role in supporting the transition to sustainable cooking, including through the wider use of climate bonds.** Scaling up sustainable cooking represents one of the most significant opportunities worldwide to generate major climate change mitigation and adaptation “win-wins”: reducing reliance on traditional fuels such as firewood and charcoal, improving human health, while helping to preserve forest ecosystems, ecological resilience, and local biodiversity. New financing mechanisms such as climate bonds could significantly expand the volume of capital flowing to the sector, and yield wide-ranging benefits for both local citizens and the global climate.

In light of the estimated EUR \$110 billion in annual costs to human health, to the environment, and to local economies caused by the use of solid fuels like wood and charcoal for cooking (GACC 2016), it is finally time that the transition to sustainable cooking be given the priority it deserves. Although this transition is still in its infancy in many parts of the world, there are promising signs that the technical and business model innovations are already available to make the transition possible worldwide. **With sufficient political will at the highest levels, combined with appropriate financial resources, it is indeed possible to imagine a world that has truly and finally evolved “beyond fire”.**



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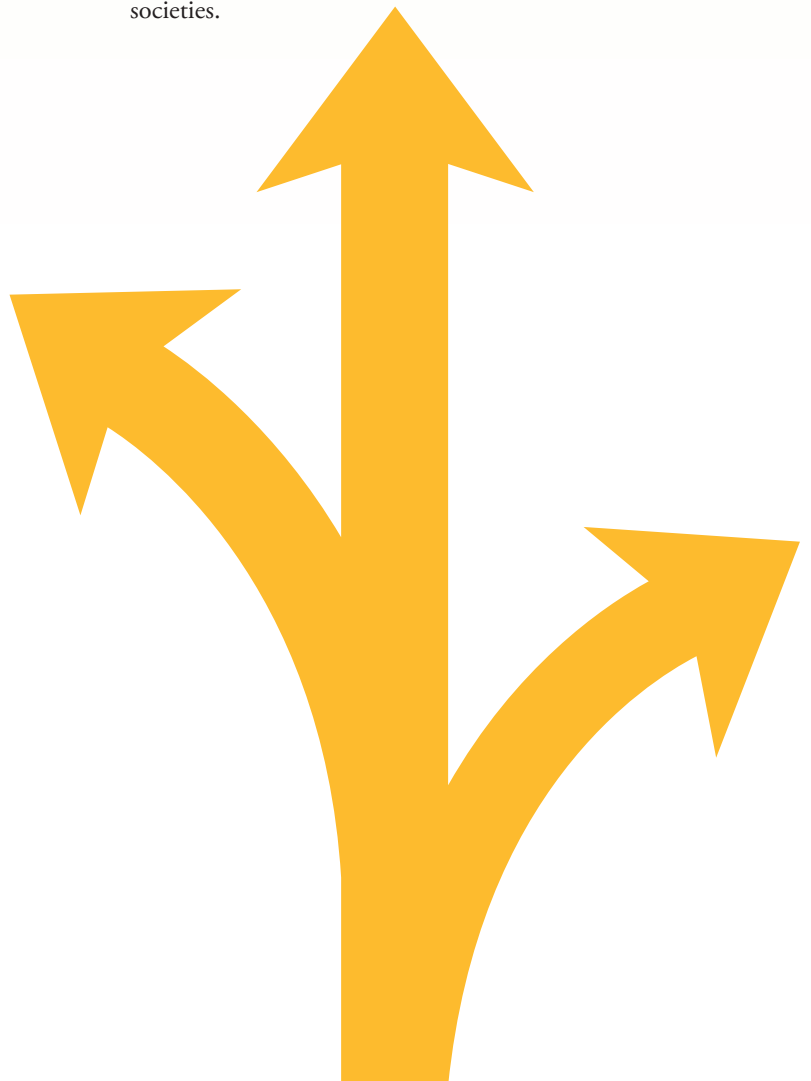
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