PBL Netherlands Environmental Assessment Agency

TOWARDS UNIVERSAL ACCESS TO CLEAN COOKING SOLUTIONS IN SUB-SAHARAN AFRICA

An integrated assessment of the cost, health and environmental implications of policies and targets

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PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. We contribute to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of our studies. We conduct solicited and unsolicited research that is both independent and scientifically sound.

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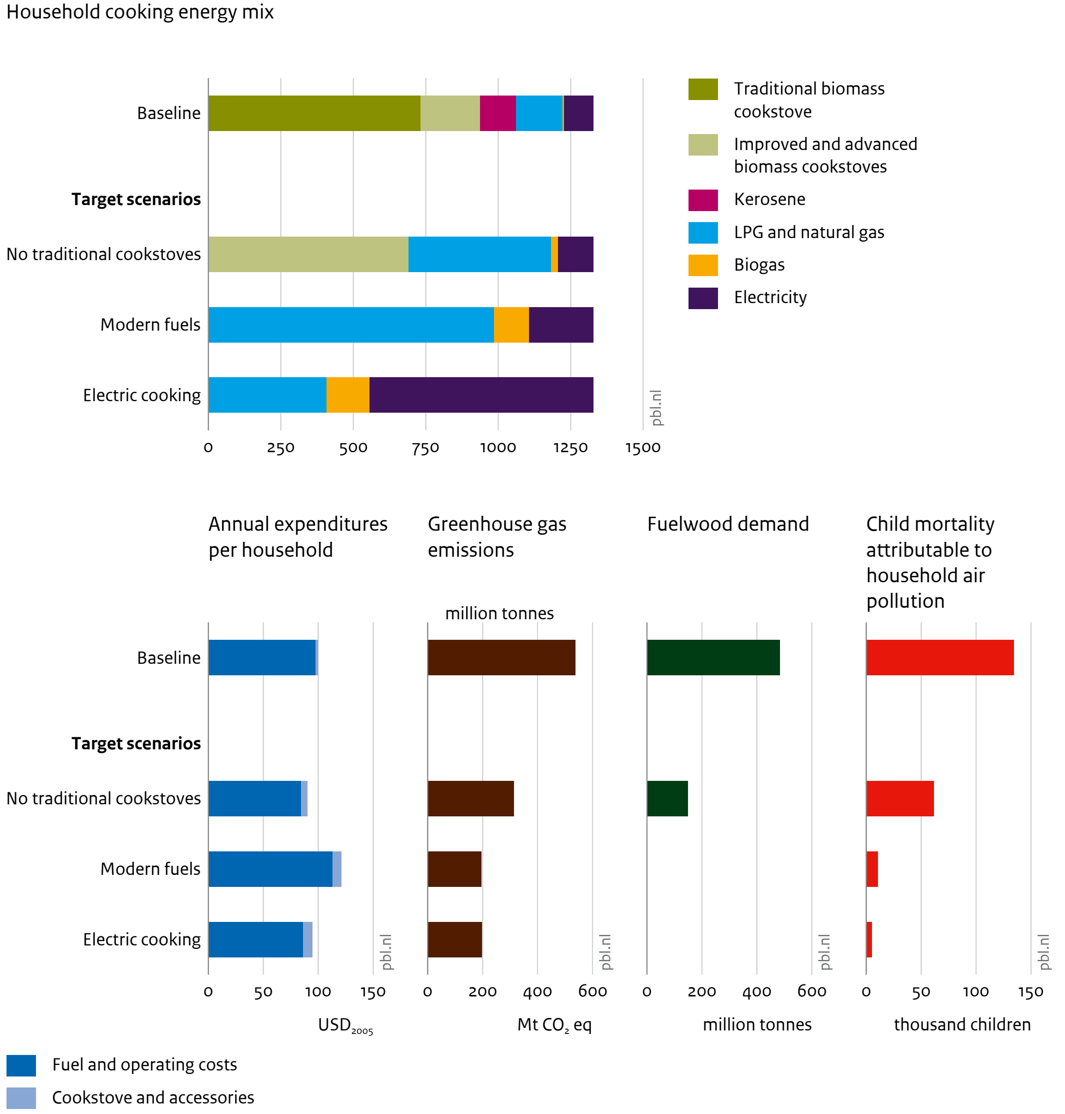
Executive Summary

Improving access to clean cooking fuels and technologies in developing countries is essential for sustainable human development.
Clean cooking is important for reducing premature deaths from poor indoor air quality, and has a range of other co-benefits related to reducing biodiversity loss and degradation, climate change mitigation, increasing gender equality and overall reduction in poverty. Globally, more than 2 billion people still use solid fuels to cook on open fires or inefficient traditional cookstoves, about 720 million of which in Sub-Saharan Africa. The estimated number of deaths due to related household air pollution in Sub-Saharan Africa ranges from 400,000 (IHME 2018) to 740,000 (WHO 2019) in 2016, between 150,000 and 250,000 of which concerned children under the age of 5. The importance of energy access is recognised in the Sustainable Development Goals (SDGs), with SDG7 aiming for 'access to affordable, reliable and modern energy services for all' by 2030.

Achieving the SDG target of universal access to clean fuels and technologies by 2030 requires a huge effort.
In the absence of coordinated action, enabling policies and scaled-up finance, the number of people in Sub-Saharan Africa relying on traditional biomass cookstoves is projected to amount to 660–820 million by 2030 (50% to 60% of the population), depending on socio-economic developments, compared to about 720 million (70% of the population) in 2016. The heavy dependence on solid biomass for traditional cookstoves is largely concentrated in rural areas, but there is also considerable use in urban areas. For rural households that do not have a stable income and want to change to cleaner cooking solutions, the purchasing costs of cookstoves and accessories form a large barrier. Furthermore, the annual fuel and maintenance costs are also believed to be high, leading to a limited adoption of such new stoves, and thus reducing the benefits of cleaner solutions in the region.

To guide effective policy-making, an integrated and systemic view on clean cooking solutions is needed.
This report explores the roles and consequences of various technologies and fuels in a transition toward universal access to clean cooking in Sub-Saharan Africa. Various scenarios are developed to explore interactions between affordability of fuels and cookstoves, the availability of fuels, as well as related impacts on health, risk of deforestation and climate change. The study aims to inform policymakers and public and private investors on investment choices and the development of effective policies to bring universal access to clean cooking solutions on track towards 2030, in Sub-Saharan Africa.

Figure 1
Implication of different pathways to clean cooking solutions, 2030



Source: PBL

The Baseline scenario assumes no specific policies to increase access to clean cooking technologies. In the No traditional cookstove scenario, traditional cookstoves (i.e. three-stone fires or locally manufactured simple cookstoves) and kerosene will be phased out, completely, by 2030. In the Modern fuels scenario, all biomass stoves will be phased out by 2030. The Electric cooking scenario, in addition to all biomass stoves being phased out by 2030, also assumes changes in cooking practices if households switch to cooking on electricity (meals that are less energy-intensive and more pre-cooked food), leading to decreased energy demand.

Phasing out the use of traditional biomass has strong benefits for human health, biodiversity and the climate…

Compared to baseline trends, completely phasing out traditional cookstoves by 2030 is projected to lead to 70% lower fuelwood demand (significantly reducing the pressure on biodiversity), 42% fewer greenhouse gas emissions, and a 55% reduction in child mortality attributable to household air pollution (Figure 1). Child mortality can decrease by 70% and emissions may reduce by 80% if the performance and use of cleaner improved and advanced biomass cookstoves, as well as those on LPG (liquefied petroleum gas), improves at a faster rate. Phasing out biomass cookstoves altogether could decrease child mortality attributable to household air pollution and total fuelwood demand to practically zero and reduce cooking-related greenhouse gas emissions by nearly 65%.

… and could lead to reduced annual cooking costs if accompanied by a change in cooking behaviour.

By far the largest share of total cooking costs is in fuel rather than the purchase of the cookstove itself (Figure 1). Although improved and advanced cookstoves carry much higher initial purchasing costs, their much higher fuel efficiency can considerably reduce annual fuel costs and thus lead to lower overall cooking costs. If the transition towards clean cooking is accompanied by a change in cooking behaviour, including the use of more processed and pre-cooked food, the resulting decreasing energy requirements could make electric cooking an interesting option for the majority of households and reduce annual cooking costs. Without such behavioural changes, phasing out biomass cookstoves would lead to an increase in total annual cooking costs, mostly in relation to fossil gaseous fuels.

Policies aimed at promoting specific clean cooking fuels or technologies may help to accelerate the transition, but have potential side effects

Subsidies for specific fuels or cookstoves can help to increase their adoption, but may also have unwanted side effects. For instance, policies aimed at increasing the use of LPG or natural gas (both liquefied (LNG) and piped natural gas) could reduce not only the use of traditional biomass cookstoves, but also that of advanced cookstoves and, in the longer term, other clean cooking solutions, such as cooking on electricity. A subsidy on improved and advanced cookstoves could lead to a strong decrease in the use of traditional cookstoves, but could also slow down a transition to even cleaner cooking fuel alternatives, such as LPG or electricity. It would be better, therefore, for policy efforts to promote a broad suite of clean cooking solutions, rather than address one specific fuel or technology.

There are several pathways to achieving universal access to clean cooking solutions. Modern fuels (e.g. LPG, natural gas, biogas and electricity) and cleaner biomass cookstoves all have a role to play in the transition.
Achieving universal access to clean cooking by 2030 is proving to be an enormous challenge. Combinations of cooking fuels and technologies may differ per local community, and may be based on income, biomass availability and/or proximity to infrastructure. Improved and advanced biomass cookstoves could play an important role in providing cleaner cooking options as an interim solution for the poorest households, mostly in rural areas. In addition, biogas could meet a considerable part of the cooking energy demand due to the abundance of biomass resources, including dung and agricultural residues. LPG, natural gas and electricity are attractive options, especially for urban areas, but also in rural areas – and certainly once traditional biomass use will have been phased out completely.

Policy efforts should focus on affordability of modern cookstoves and make clean fuels affordable and accessible.
It is crucial that challenges regarding the affordability of modern cookstoves are addressed and ownership is facilitated through appropriate and targeted financing and/or grant mechanisms, without disrupting the market. Crucial components of the transition, in addition to direct financial support, also need to include raising awareness among consumers to ensure that cookstoves are used correctly and consistently, and stimulating research and development in cookstove technology to improve their efficiency and affordability.

All this requires a clear strategy and coordinated efforts by all stakeholders involved.
Achieving universal access to clean fuels and technologies by 2030 requires rolling out clean fuel infrastructure, rapidly and at an unprecedented scale. This requires facilitating access to financing for both retailers and end users, implementing stringent policy to halt the use of solid biomass in inefficient and highly polluting traditional stoves, creating awareness about the benefits of clean cooking, and improving the performance of the advanced biomass and modern stoves in the market. This calls for targeted policy, significant efforts by all players, better alignment of incentives, scaling up investments in clean cooking fuels and technologies, and an integrated approach to policy and regulations. This would involve strong partnerships between government authorities, bilateral and donor organisations, NGOs, community-based organisations, academia, the private sector and local communities.

FULL RESULTS

1 Context and objectives

Modern energy services are essential for human development and environmental sustainability
Energy systems play a central role in economic development and social progress, without which it is impossible to raise living standards, drive inclusive economic growth and aim for sustainable development (GEA, 2012). At the household level, both access to electricity (Lucas et al., 2017) and the use of clean fuels and technologies for cooking and heating are important. However, more than three billion people are currently still relying on traditional biomass (wood, charcoal, dung, agricultural residues) for cooking, with various negative side effects.
Inefficient and incomplete combustion of traditional biomass (e.g. fuelwood, charcoal, dung and agricultural residues) is associated with high levels of hazardous air pollutants, including carbon monoxide and fine particulate matter (Schlag and Zuzarte, 2008), increasing the risk of, for example, acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD), lung cancer and cataract (Stanaway et al., 2018). Furthermore, the use of fuelwood and charcoal may exert large pressures on the local and regional environment, including those of deforestation, forest degradation and destruction (Karekezi et al., 2012), soil degradation and erosion (IEA, 2006). Finally, black carbon emissions related to household biomass burning, and net CO_2 emissions related to unsustainably harvested biomass both contribute to climate change (Pearson et al., 2017).

Improving access to clean cooking technologies is an international development priority that has many co-benefits, but the challenge is massive
The importance of energy access for sustainable development was first recognised by the international community through the Sustainable Energy for All (SEforALL) initiative, and later integrated in the Sustainable Development Goals (UN, 2015). SDG target 7.1 aims for 'universal access to affordable, reliable and modern energy services' by 2030, including clean cooking fuels and technologies. Given the negative side effects of cooking on traditional biomass for human health and the environment, a transition towards clean cooking solutions may contribute to achieving a range of other SDGs as well (GCCA, 2016; Rosenthal et al., 2018a). However, so far, efforts to improve the use of clean cooking solutions in developing countries has been outpaced by population growth (IEA, 2017). In its recent World Energy Outlook, the IEA estimates that, by 2030, 2.2 billion people will still lack access to clean cooking technologies, globally (IEA, 2018). Today, there are little more than 10 years left to increase efforts and achieve the SDG target.

Box 1: Cookstove fuels and technologies

Various fuels are used for cooking, including solid fuels (e.g. coal, firewood, agricultural residues, dung and charcoal), liquid fuels (e.g. kerosene, methanol, ethanol and plant oil), gaseous fuels (e.g. biogas, liquefied petroleum gas (LPG) and natural gas) and electricity. There are also several types of cookstove technologies in use, ranging from the most basic three-stone fires to advanced biomass cookstoves, and from cookstoves using liquid or gaseous fuels to electric or induction cookers. These fuel and technology choices generally differ in fuel efficiency levels (an important indicator, as a higher efficiency implies a lower demand for fuel) and air pollutant emissions (an important indicator for health effects).

The WHO compiled and reviewed the evidence on the impacts of household solid fuel combustion on child and adult health, and developed air quality guidelines (AQGs) for specific pollutants (WHO, 2014). Furthermore, the WHO also set air quality guidelines for air pollutant concentrations (WHO, 2006).

Table 2 provides an overview of the most used fuel and cookstove combinations, together with their conversion efficiencies and characteristic $PM_{2.5}$ concentrations. Electricity is the cleanest cooking solution, with no air pollutant emissions, at the household level, and a very high conversion efficiency (although there are greenhouse gas emissions and conversion losses involved in the generation of electricity). Gaseous fuels, such as natural gas or biogas, are considered clean with respect to household air pollution, with indoor $PM_{2.5}$ concentration levels that are generally below the WHO guideline of annual mean 10 µg/m^3. LPG is also considered a clean fuel, with indoor $PM_{2.5}$ concentration levels that are possibly above the WHO guideline of 10 µg/m^3, but below the interim 1 target of 35 µg/m^3. Kerosene is not regarded a clean fuel, because when used in combination with cheap wick cookstoves it can produce high levels of air pollutants, significantly exceeding the WHO interim 1 target. Advanced cookstoves maximise combustion, resulting in a much lower emission level than traditional or improved cookstoves, but still leading to $PM_{2.5}$ concentration levels above the WHO interim 1 target.

Table 1
Overview of cooking fuel and technology combinations used in this study

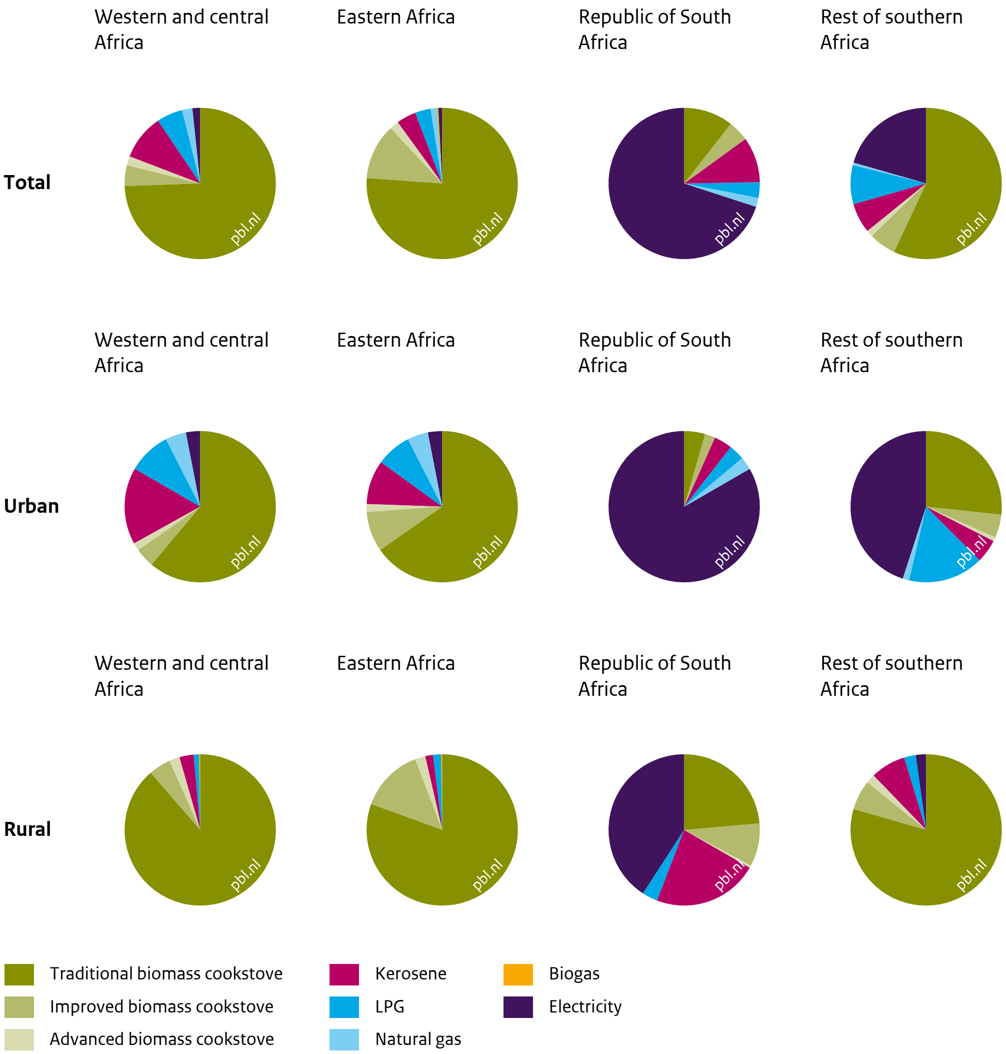
Fuel	Cookstove technology	Conversion efficiency (%)	24-hour $PM_{2.5}$ concentrations ($\mu g/m^3$)
Traditional biomass (charcoal, firewood, agricultural waste, animal dung)	Traditional cookstove	<15	> 500
	Improved cookstove	25–35	110–500 (firewood) 35–70 (charcoal)
Modern biomass (briquettes, pellets)	Advanced cookstove	35–45	35–110
Coal	Improved coal cookstove	25–35	110–500
Kerosene	Kerosene stove	35–55	20–80
LPG	Single or double burner	50–60	5–35
Natural gas	Gas stove	50–60	< 5
Biogas (based on e.g. animal dung and agricultural and kitchen waste)	Gas stove plus digester	40–60	< 5
Electricity	Electric/ induction	75–90	< 5

Based on Bruce et al. (2017), Kaygusuz (2011) and World Bank (2014)

Achieving the SDG target on clean cooking is particularly challenging in Sub-Saharan Africa
In 2016, around 800 million people in Sub-Saharan Africa (77% of the population) were relying on solid biomass for their primary cooking energy source (Figure 2), mainly in inefficient stoves or traditional three-stone fires. This is a decline of only 3 percentage points since 2000 (IEA, 2017). The use of traditional biomass is particularly dominant in poor rural settlements because of its low cost (sometimes collected for free), the lack of available alternatives, and sometimes because of cultural factors (e.g. preferences and taste). Gaseous fuels (LPG and natural gas), which are considered clean, are barely used in rural areas, mainly due to the lack of a distribution system and the relatively high and fluctuating price of the fuel in combination with very low income levels. Finally, electricity, the cleanest cooking solution with respect to household air pollution, is primarily used in southern Africa.

Household air pollution is estimated to have caused almost 400,000 deaths in 2016, around 150,000 of which were children under the age of 5 (Institute for Health Metrics and Evaluation (IHME) 2018). Furthermore, the production and use of traditional biomass (including charcoal) is estimated to involve more than 300 million tonnes of wood, annually (Lambe et al., 2015), outpacing the biomass regrowth rate in large parts of the continent (Bailis et al., 2015). Several countries in Sub-Saharan Africa have set ambitious targets for access to clean cooking. Rwanda and Cape Verde, for instance, are aiming for 100% access to clean cooking by 2025, while several other countries recognise the importance of access to clean cooking in their Nationally Determined Contributions (NDCs) to the Paris Agreement.

Figure 2
Regional cooking energy mix in Sub-Saharan Africa, 2016



Source: Casteleyn 2017; Smeets et al. 2017

A range of clean cooking options exist, but they differ strongly in cookstove and fuel costs, health implications and environmental impact

Significant improvements with respect to clean cooking can be made when switching to improved or advanced biomass cookstoves. These stoves still use biomass but perform better in terms of efficiency and air pollution. And although they are much more expensive than the traditional stoves (most of which are built locally), this could be compensated for by reduced fuelwood requirements. Alternatively, liquid fuels, such as LPG or LNG (liquified natural gas), perform much better with respect to air pollution than biomass cookstoves, but are currently more costly options and require infrastructure and markets and that are currently not in place, especially not in rural areas. Other clean alternatives include the use of biogas or electric cooking, options that rely less on fossil fuels and thus generate fewer greenhouse gas emissions. However, biodigesters are expensive, while availability of both could be an issue depending on electricity access or the availability of biogas sources (agricultural and other waste).

A thorough assessment is required to understand possible transition pathways to universal access to modern cooking solutions in Sub-Saharan Africa

There are many programmes that promote clean cooking in Sub-Saharan Africa; however, these programmes are focusing on specific technologies rather than considering a range of solutions for various settings. Moreover, the efforts are fragmented and lack alignment of resources and competencies of the various actors. Similarly, there are several studies that analyse the roles of various technologies for clean cooking in Sub-Saharan Africa (Amiguna and von Blottnitz, 2010; Brown et al., 2017; Rosenthal et al., 2018; Zubi et al., 2017), but a comprehensive study that looks at various transition pathways, and provides a quantification of the synergies and trade-offs with other sustainable development issues, is currently missing. In this context, the Directorate-General for international Cooperation (DGIS) of the Dutch Ministry of Foreign Affairs asked PBL Netherlands Environmental Assessment Agency to conduct an integrated analysis of pathways towards clean cooking in Sub-Saharan Africa, which addresses the roles of various technologies and actors. The analysis should help the Dutch Government in achieving its target of providing 50 million people, worldwide, with access to renewable energy by 2030 (BZ, 2015).

For this study, quantitative scenarios were developed to explore transition pathways to universal access to clean cooking technologies in Sub-Saharan Africa

The scenarios take into account current and future developments in fuel availability and costs, and purchasing costs for stove technologies, under various policy and target assumptions. They focus on an integrated and systemic view on modern cooking solutions, by exploring the interactions between affordability of fuels and cookstoves, availability of fuels, and related climate change, risk of biodiversity loss, and health implications. The study aims to inform the international debate and, more importantly, policymakers and public and private investors, in making holistic investment choices and developing effective policies to bring universal access to clean cooking on track towards 2030.

2 Methodology and main assumptions

Model-based scenario analysis can provide a consistent picture of current and future cooking challenges, implications of specific targeted policies and the efforts needed to realise specific targets. Here, we discuss the various models used in our analysis, as well as the most relevant technology, costs and socio-economic assumptions.

2.1 Model description

For the scenarios analyses, the IMAGE 3.0 integrated assessment modelling framework was used (Stehfest et al., 2014), which includes the TIMER energy-system simulation model (Van Vuuren et al., 2006) and the GISMO health model (Lucas et al. Submitted). Future developments in household energy demand, the cooking energy mix and related cookstove purchasing costs and fuel costs were analysed with the residential sector end-use model (REMG), which is part of the TIMER model (Daioglou et al., 2012). Parts of the IMAGE model were used to assess total renewable biomass availability, while the GISMO model was used to assess child mortality implications. The strength of the IMAGE modelling framework is that it allows looking at the various aspects related to the transition toward sustainable access to modern energy in an integrated way, including energy demand and supply, the availability of agricultural residues, fuelwood and charcoal, greenhouse gas emissions related to cooking, and child mortality impacts as a result of household air pollution.

The TIMER model describes demand and supply of key energy carriers for 26 world regions (Van Vuuren et al., 2006). Important issues that can be addressed with the use of the model include transitions to modern and sustainable energy supplies, energy access and future demand projections, and the role of the energy conversion sector and various energy technologies in achieving a more sustainable energy system. The REMG model describes household energy demand and the fuel mix for five income classes, for both rural and urban households. REMG is a stylised bottom-up simulation model, which describes energy demand for five end-use functions, including cooking (Daioglou et al., 2012).

Household size and income are the model's primary drivers of cooking energy demand (Figure 3). The model includes the following cooking fuels: coal, traditional biomass (in combination with traditional and improved cookstoves), modern biomass (in combination with advanced cookstoves), kerosene, LPG, biogas, natural gas and electricity.

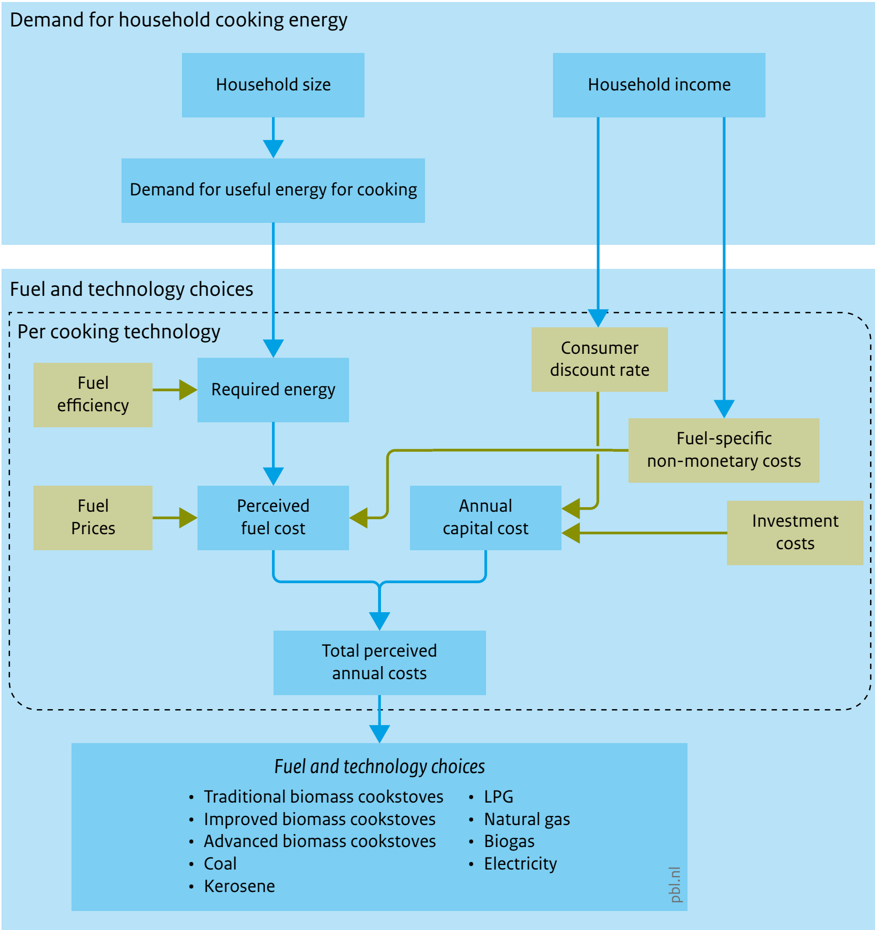
The model uses a vintage capital model for the stock of stoves. Shares of different types of stoves in the cooking energy mix are the result from additional purchases and depreciation after their technical lifetime. Market shares of purchases are determined using the monetary and non-monetary costs of various cooking technologies with a multinomial logit allocation. The model thereby assigns the largest market share to the cheapest energy technologies, but technologies that have higher costs are also awarded a certain share, taking into account heterogeneous local characteristics, where relevant.
These costs include monetary and non-monetary costs. The monetary costs are the sum of the annual capital and operating (fuel and maintenance) costs. Annual capital costs include the costs of the cooking technology and accessories and consumer discount rates. The discount rates are higher for low-income households and decrease as income levels increase. The non-monetary costs represent the fact that people's choice for a certain fuel is not only determined by economic factors; especially with respect to poorer households, where cultural aspects, lack of awareness about the advantages of cleaner fuels, and the opportunity cost related to traditional biomass also play an important role. It is assumed that the non-monetary costs of traditional fuels (i.e. biomass, kerosene) increase with income.

The IMAGE model is a simulation model that represents certain interactions between society, the biosphere and the climate system, and is used to assess sustainability issues such as climate change, biodiversity loss and human well-being. The model includes a detailed description of the energy and land-use system and simulates socio-economic and environmental parameters on a geographical grid of 30 x 30 minutes or 5 x 5 minutes (around 50 km and 10 km at the equator, respectively), depending on the specific variable. For this analysis, the model was primarily used to determine wood demand and supply.

The GISMO health model describes the causal chain between health-risk factors, morbidity and mortality, based on a multi-state approach, distinguishing risk exposure, disease incidence and death (Lucas et al. Submitted). We used the GISMO model to assess future developments in child mortality attributable to household air pollution. The model was updated to include total deaths from acute lower respiratory infections (ALRI) and relative risk (RR) ratios for the various cooking technologies, based on the 2017 study on the Global Burden of Disease (Stanaway et al., 2018). RR ratios indicate the increased risk of falling ill or dying while exposed to a certain risk factor, as compared to a situation with no increased risks, which in this context means no household air pollution (RR=1).

Important inputs in the model framework are descriptions of the future development of direct and indirect drivers of household energy demand, including exogenous assumptions on population, urbanisation, economic development, technological change (including the efficiency and costs of various cooking technologies) and specific policies or policy targets.

Figure 3
Drivers of the choice of household cooking technology

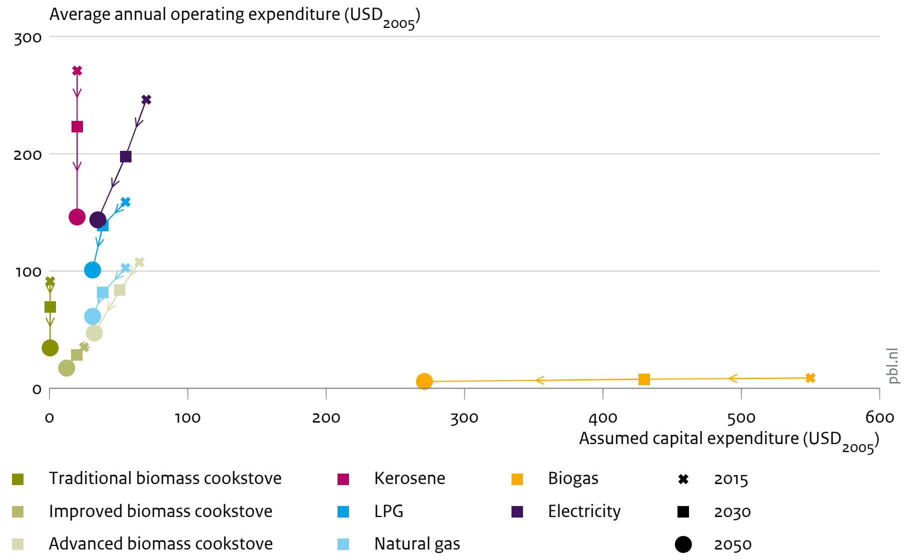


Source: PBL

2.2 Technology and cost assumptions

The most important assumptions in the REMG model concern current and future costs of fuels and cookstoves. Together with household per capita income levels, these determine the choices of cooking technology in the model. Figure 4 shows assumed current and future average capital costs (for stoves and accessories) and the average annual operating costs (for fuel and maintenance) which include cooking fuel and technology combinations. These costs may differ per region and between urban and rural areas. The values are averages across the whole of Sub-Saharan Africa.

Figure 4
Capital and operating expenditures on cooking technologies in Sub-Saharan Africa



Source: Daioglou 2010; Jeuland and Pattanayak 2012; Jeuland and Soo 2016

For all cooking solutions except biogas, annual operating costs are higher than the initial capital costs of purchasing the cookstove. Kerosene and electricity, especially, involve high operating costs, followed by LPG. The annual operating costs related to biogas are close to zero, but the initial capital costs are high, especially those related to the digester. Traditional cookstoves, kerosene and coal are considered mature technologies and, therefore, are assumed not to decrease any further in price. LPG and natural gas cookstoves are also relatively mature technologies and, therefore, are assumed to have only a relatively modest annual cost decline of 1%, up to 2050. For the other cooking technologies – electricity, improved and advanced cookstoves and biogas – an average annual capital cost decline of 2% is assumed.

The price of biodigesters in 2015 was USD 550 and declines an average of 2%, annually (Daioglou, 2010; Jeuland and Soo, 2016; Jeuland and Pattanayak, 2012). Other important assumptions include the conversion efficiencies of fuels and technology related household air pollution (focused on $PM_{2.5}$ concentrations). Conversion efficiencies determine secondary energy demand (e.g. amount of wood for traditional biomass) and, thus, also the operating costs as well as total greenhouse gas emissions and potential deforestation. Household air pollution typically concerns $PM_{2.5}$ concentrations for the various cooking technologies. Current values for conversion efficiencies are based on the middle or low end

Table 2

Assumptions on efficiency levels and health effects of various cooking technologies

Fuel	Cookstove technology	Conversion efficiency (%)			24-hour $PM_{2.5}$ concentrations ($\mu g/m^3$)		
		2015	2030	2050	2015	2030	2050
Traditional biomass	Traditional cookstove	12	14	20	500	500	500
	Improved cookstove	30	33	40	200	150	75
Modern biomass	Advanced cookstove	40	47	65	75	60	35
Coal	Improved coal cookstove	25	25	25	200	150	75
Kerosene	Kerosene stove	35	44	55	50	40	20
LPG	Single or double burner	50	58	70	20	10	5
Natural gas	Gas stove	50	57	66	0	0	0
Biogas	Gas stove & digester	40	50	65	0	0	0
Electricity	Electric/ induction	75	86	90	0	0	0

Conversion efficiencies are based on Bruce et al. (2017) and Kaygusuz (2011); health effects are based on World Bank (2014).

of the range as reported by the literature and, for the $PM_{2.5}$ concentrations, on the middle end of this range (see Table 2). For future values, we assumed that conversion efficiencies and $PM_{2.5}$ concentrations improve towards the respective high and low end of the reported ranges.

Greenhouse gas emissions from cookstoves vary depending on fuel type and cookstove efficiency. Emissions related to coal, biomass, kerosene, LPG and natural gas were calculated on the basis of the emission factor given in Annex 2 and the total energy input required to produce the desired amount of useful energy. For electricity, emissions were calculated on the basis of the secondary energy input required and the baseline regional projections of emissions from electricity generation (including efficiency and transmission losses). For biomass cookstoves, we assumed net CO_2 emission at the point of combustion of fuelwood to be zero, if the wood was sustainably harvested. Based on FAO estimates (FAO, 2017), we assumed a third of the fuelwood to be harvested unsustainably, which therefore adds additional CO_2 emissions to the atmosphere.

Finally, assumptions about the amount of useful energy needed for cooking are important for determining the technology choice. The amount of energy that a household requires for cooking has been the subject of numerous studies, and large differences are found in the estimates, ranging from 0.36 MJ/capita/meal to 6 MJ/capita/meal. Balmer (2007) found that, in households that have access to modern cooking fuel and technology, the cooking fuel consumption is in the range of 2 to 3 MJ/capita/day. Based on a field study in Nyeri County, Kenya, Fuso Nerini et al. (2017) arrive at the conclusion that one ‘standard’ meal for a household of four requires 3.64 MJ of energy. Similarly, the UN assumes an average cooking energy requirement of 50 kgoe per person per year, which is equivalent to 5.8 MJ per person per day (UN, 2010). On the other hand, Zubi *et al.* (2017) estimate that a 3-litre multi-cooker requires only 0.6 kWh per day to cook one lunch and one dinner for a household of six, which is equivalent to 0.36 MJ/capita/day. This range in required cooking energy makes it difficult to estimate location-specific energy demand. Moreover, Daioglou *et al.* (2012) found no statistically significant relationship between energy for cooking and income or geographical region. Hence, we used a constant value of 3 MJ/capita/day of useful energy for all households and regions. More detailed assumptions regarding the energy content and greenhouse gas emissions of the various energy technologies used can be found in Annex 2.

2.3 Scope and limitations

Several studies show the role of monetary value of fuel (Morrissey, 2017), household income (Makonese et al., 2018) and infrastructure (Hou et al., 2017) in obtaining modern cooking energy and related technologies. However, these relationships might be different in the future and it is well-studied that household fuel choices are influenced not only by income and urbanisation but also by social, cultural and technical determinants. Other factors that also play a significant role in cooking fuel and technology choices include gender (Karimu et al., 2016) and age (Kelebe et al., 2017) of the household head, cultural preferences (Toonen, 2009), education (Mekonnen and Köhlin, 2008) and technical aspects of the cookstoves (Masera et al., 2005; Nlom and Karimov, 2015; Shen et al., 2015). Our model does not explicitly address the role of these determinants. Furthermore, our analysis is based on a household's primary choice of cooking fuel, whereas empirical studies show that achieving access to clean cooking is not a binary process, and households do not wholly abandon one fuel in favour of another, but rather that modern fuels are slowly integrated into energy-use patterns. This results in a mix of traditional and modern cooking fuels; a phenomenon referred to as 'fuel-stacking'. Due to data limitations and the resulting complexity of the model, our model does not capture this phenomenon. The results of the analysis are driven by the underlying data, which is collected from several sources that often use various methodologies and inconsistent definitions of variables. In addition, the model's projections and our analysis cover neither the implementation nor the financing of these scenarios.

3 Scenario descriptions

Various pathways to clean cooking can be envisaged, with varying implications for the efforts required (in terms of purchasing price and fuel costs), as well as for the projected health and environmental benefits. A large-scale shift from traditional biomass to clean fuels or electricity brings about the largest reductions in household air pollution and, thus, the most significant health improvements (Morrissey, 2017). However, in large parts of Sub-Saharan Africa, a reliable supply chain for clean fuels is not yet available, while nearly 35% of the region's population is projected not yet to have access to electricity by 2030, without specific policies to improve this (Dagnachew et al., 2017). It is therefore useful to analyse scenarios with various target levels for clean cooking, which also allows analysing synergies and trade-offs for various ambition levels. The scenarios were designed on the basis of discussions with stakeholders and can be categorised as policy scenarios and target scenarios. The policy scenarios were designed to assess the effect of specific policy interventions, whereas the target scenarios show the cost-optimal way to achieve specific predefined targets. Table 3 summarises the scenarios, with a more detailed scenario narrative provided below.

3.1 Baseline scenario

The baseline scenario shows future cooking patterns without any specific, related policy interventions, based on historical relationships between per-capita income and cooking technologies. All results under the policy and target scenarios (i.e. technology and fuel use, purchasing costs, fuel costs, health effects, biodiversity effects) should be interpreted relative to baseline developments. The differences in the results between baseline and policy scenarios show the effects of the implemented policies, whereas the differences in the results between baseline scenario and target scenarios show the changes that are needed to achieve the predefined targets.

3.2 Policy scenarios

We analysed three policy scenarios; one in which a 50% capital subsidy on improved and advanced cookstoves is implemented (*cookstove subsidy*), one in which a 50% capital subsidy on biodigesters is implemented (*biodigester subsidy*), and one in which the distribution of LPG and natural gas is enhanced (*enhanced distribution*).

The idea behind the *cookstove subsidy* scenario is that, in the short term, a complete transition to very clean fuels and technologies is not feasible. The focus in this scenario is therefore

Table 3
Names and descriptions of the scenarios for Sub-Saharan Africa

Scenario set	Scenario name	Short description
Baseline scenario	Baseline	Reference scenario without specific policies to stimulate clean cooking.
Policy scenarios	Cookstove subsidy	A 50% subsidy on the retail prices of improved and advanced cookstoves, but no subsidy on fuel.
	Biodigester subsidy	A 50% subsidy on the retail price of biodigesters.
	Enhanced fuel distribution	Part of the LPG (liquefied petroleum gas) and LNG (liquefied natural gas) required for cooking is provided through infrastructure support or subsidies (40% in urban areas and 100% in rural areas).
Target scenarios	No traditional cookstoves	All households that rely on solid biomass in combination with a traditional cookstove have switched to cleaner cooking technologies by 2030.
	Modern fuel	The use of solid biomass, kerosene and coal for cooking will be eliminated by 2030.
	Electric cooking	The use of solid biomass, kerosene and coal for cooking will be eliminated by 2030. Households cooking on electricity will use 50% less energy due to changes in cooking behaviour.

to promote improved and advanced cookstoves for households that currently apply the worst cooking methods.

The idea behind the *biodigester subsidy* scenario is that in rural poor communities, excess fuel in the form of agricultural and other waste is available which currently is not being utilised. Biodigesters could convert these types of waste into biogas which can be used for cooking. Biogas technology is very attractive for rural settlements, since the fuel source is produced locally, the fuel is typically free, abundantly available and requires little time to collect, the gas burns efficiently and leads to almost no pollution. However, currently, biodigesters are very expensive for these households. The focus in this scenario is therefore on promoting the purchase of biodigesters so that the available waste can be converted into biogas.

The motivation for the *Enhanced fuel distribution* scenario is that LPG has attracted much support as a potential substitute for solid biomass, especially in urban areas. However, the weak supply chain and the high and often fluctuating price of this fuel has limited its diffusion rate in Sub-Saharan Africa. In addition, the initial capital costs of stove and components and deposit for the gas cylinder has put LPG beyond the reach of the rural poor, which suggests that an innovative business model or some form of financial support could help to improve access. The same can be said about natural gas. To address these concerns, we have explored the role of natural gas and LPG when the supply chain is subsidised by the government and/or other players in the sector under a distribution programme. In our model, it is implemented by assigning a certain part of the total useful energy demand (100% for rural households and 40% of the poorest urban households) to benefit from the enhanced fuel distribution system. This programme will lower gaseous fuel prices for the final consumer (by on average 20% to 30% for LPG and 30% to 50% for natural gas).

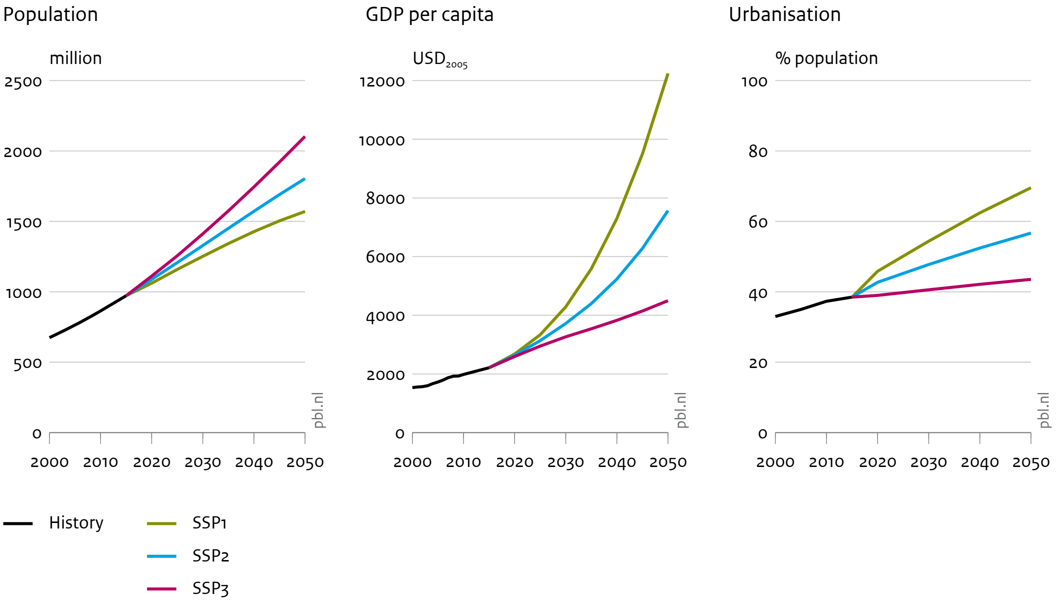
3.3 Target scenarios

In the No traditional cookstoves scenario, a predefined target is set so that traditional cookstoves and kerosene will be completely eliminated by 2030. Similar to the other target scenarios, there is not much of a narrative behind this scenario; instead, the scenario should be regarded as providing insight into what would be involved, in terms of technology and purchasing and fuel costs, for the dirtiest of cooking methods to be abolished completely by 2030 – and what the potential effect would be on human health and biodiversity.

The Modern fuel scenario sets a more ambitious predefined target, namely the complete phasing out of all solid fuels and kerosene by 2030.

The Electric cooking scenario is based on the idea that, together with the adoption of the cleanest cooking technology (electricity), people's cooking behaviour will change, as well. This assumption is reinforced by the declining price of off-grid renewable energy technologies, which makes them competitors of charcoal and firewood (Brown et al., 2017). In this scenario, we assumed 50% lower energy use for households cooking on electricity, together with the predefined target to eliminate all solid biomass and kerosene by 2030. This scenario could be interpreted as a change towards less energy-intensive preparation of food for those households that cook on electricity, or an increased usage of more pre-cooked foods for those households. Indeed, there is some evidence that alternative electric cooking methods can lead to much lower energy use. Zubi et al. (2017), for instance, discuss the option of an efficient electric multi-cooker running on a solar home system that would require just 0.36 MJ/capita/day to cook lunch and dinner, although Batchelor (2015) estimate a higher electricity demand of 1.2 MJ/capita/day. Both estimates are much lower than our default assumption of 3 MJ/capita/day. These low demand estimates allow coupling cooking services with mini- and micro-grids, as well as high capacity solar home systems.

Figure 5
Population, GDP and urbanisation projections for Sub-Saharan Africa



Source: SSP database

3.4 Socio-economic developments

The future demand for various cooking technologies depends on future socio-economic developments. We have based the socio-economic developments on the Shared Socio-economic Pathways (SSPs). The SSPs are five distinct global pathways describing the future evolution of key aspects of society that together imply a range of challenges for mitigating and adapting to climate change (Riahi et al., 2017; Van Vuuren et al., 2017). Each SSP is described by quantifications of future developments in population by age, sex, and education, urbanisation, and economic development, and by a descriptive storyline to guide further model parametrisation (see Box 2 and O'Neill et al., 2017). To assess future developments in household cooking demand without additional policies (baseline scenario), socio-economic projections of SSP1–3 are used (Figure 5). This allows assessing the implications of uncertainties in socio-economic developments. The policy and target scenarios are based on the SSP2 'middle-of-the-road' socio-economic projection.

Box 2: Description of the socio-economic projections

SSP1 (Sustainability): Describes a in which the world makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Educational and health investments accelerating the demographic transition, leading to relatively low mortality. Economic development is high and population growth is low.
SSP2 (Middle-of-the-road): Describes a future in which trends typical of recent decades continue (business as usual), with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Fertility and mortality are intermediate and also population growth and economic development are intermediate.
SSP3 (Fragmentation): Describes a that is fragmented, characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. The emphasis is on security at the expense of international development. Mortality is high everywhere, while fertility is low in rich OECD countries and high in most other countries. Economic development is low and population growth is high.

4 Pathways towards clean cooking

This chapter provides the quantitative results for the baseline scenarios (developments without additional policies), policy scenarios (including specific policies to promote the use of modern cooking technologies) and target scenarios (achieving universal access to modern cooking technologies by 2030). The scenarios are discussed in terms of future developments in the use of cooking fuels and technologies, related fuel costs and purchasing costs of stoves and accessories, and their implications on the risk of deforestation, greenhouse gas emissions and child health.

4.1 Future access to clean cooking without additional policies

Long-term projections are surrounded by many uncertainties, amongst others by socio-economic drivers, such as population growth and economic development. The potential effect of these uncertainties on cooking habits can partially be addressed by analysing future implications under alternative socio-economic developments. Here, we discuss future developments in cooking technologies, assuming no additional policies, based on three alternative socio-economic developments (see Box 2): SSP2 (middle of the road), SSP1 (sustainable) and SSP3 (fragmented).

Differences in socio-economic drivers increase over time under alternative developments
The policy and target scenarios, as discussed in the next section, are all based on the socio-economic assumptions of the SSP2 'middle-of-the-road' scenario, characterised by medium assumptions on population growth, urbanisation and economic development. The SSP1 socio-economic developments are characterised by low population growth and high urbanisation and economic development, while the SSP3 socio-economic developments are characterised by high population growth and low urbanisation and economic development. The projected population in Sub-Saharan Africa ranges from 1.5 billion under SSP1 to more than 2 billion under SSP3 by 2050, GDP per capita ranges from USD 4,500 under SSP3 to USD 12,240 under SSP1, and urbanisation from 44% in SSP3 to 70% in SSP1 (Figure 6). The projected socio-economic differences for 2030 between the SSPs are much smaller.

Traditional cookstoves will remain by far the most important cooking technology in 2030, without specific policies to increase access to cleaner technologies or fuels

Figure 6 shows the projected use of various cooking technologies by 2030 and 2050, under the three alternative socio-economic developments. Without additional policies, only a moderate switch away from traditional cookstoves is projected for 2030. As the population and GDP projections do not diverge strongly by 2030, the demand for fuelwood and total greenhouse gas emissions differ only slightly among three socio-economic scenarios. Although the share of solid biomass used in traditional cookstoves is projected to decline gradually, strong population growth offsets efforts to increase access to modern cooking facilities, resulting in an increase in the absolute number of people cooking on traditional cookstoves. The share of the population relying on solid biomass for traditional cookstoves declines from 70% in 2010 to between 53% and 58% by 2030, which will leave 660 to 820 million people relying on solid biomass for traditional cookstoves. This is in line with the IEA projections that, under continuation of current policies, almost 820 million people still will not have access to clean cooking fuel by 2040 (IEA, 2018).

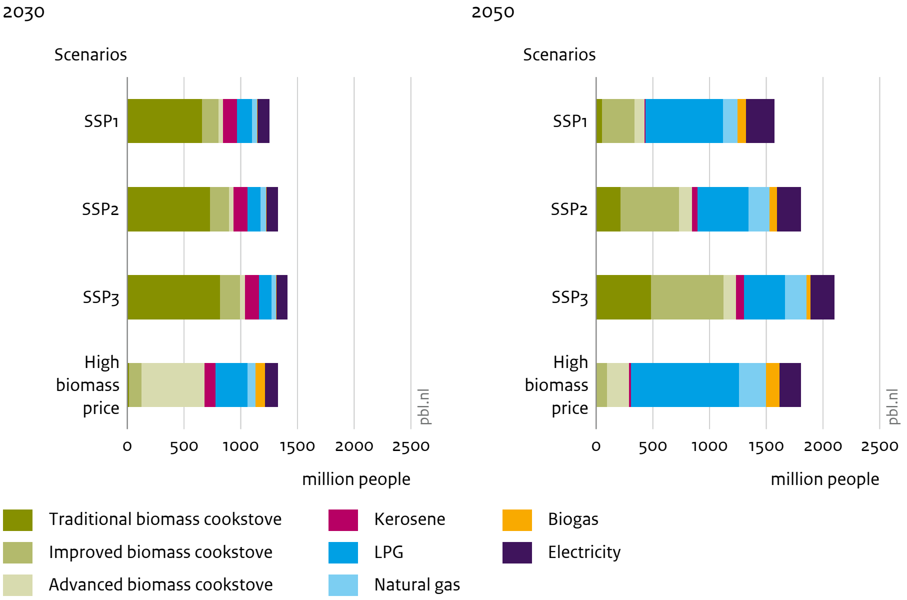
By 2050, a significant decrease in the use of traditional cookstoves is projected

After 2030, a significant decrease in the population using traditional cookstoves is projected in all three socio-economic scenarios. Traditional biomass cookstoves are mainly replaced by improved cookstoves and LPG. This rapid decrease can be attributed to i) efficiency improvements of modern fuel-based technologies and improved and advanced cookstoves, ii) urbanisation, and iii) the increase in household income. In general, a transition away from solid biomass can be faster in urban areas than in rural areas, as a result of higher income levels, longer supply chains for firewood and charcoal, and more developed markets of modern cooking fuels in urban areas. However, the long-term projections strongly depend on the socio-economic assumptions. Under SSP1 'sustainable' socio-economic developments, traditional cookstoves are projected to be almost completely phased out by 2050, while under the SSP3 'fragmented' socio-economic developments, a quarter of the population is projected to still use traditional cookstoves, most of them living in rural areas. In the latter scenario, economic development and urbanisation rates are relatively low, implying slow modern fuel infrastructure development, inability to pay for more expensive fuels and/or higher upfront stove costs, and low awareness about the benefits of modern cooking fuels. Clearly, this indicates that under unfavourable socio-economic trends, the challenge of universal access to clean cooking becomes much larger.

A much faster shift away from traditional cookstoves can be expected if biomass costs would reflect their full social costs

The above results assume average costs of traditional biomass of USD 0.03 per kilogram. To show the importance of the costs of traditional biomass on the scenarios results we have analysed an additional scenario, that assumes a higher biomass price of USD 0.28 per kilogram. This higher price better reflects the opportunity cost, health implications and environmental impact of collecting and cooking with traditional biomass.[1] The 'high biomass price' scenario is based on the SSP2 'middle-of-the-road' socio-economic

Figure 6
Impact of socio-economic developments on cooking fuel and technology choices in Sub-Saharan Africa



Source: PBL

scenario. As a result of the much higher costs of traditional biomass, the scenario shows much faster phasing out of traditional cookstoves, a tripling of households using biogas, and a doubling of gaseous fuel use by 2030. While traditional biomass still serves as primary cooking energy for about 55% of the households, this is much lower than the 70% in the baseline. Although the price for traditional biomass is increased considerably, it remains lower than for alternative fuels in the period 2016–2030, explaining the still relatively high share.

After 2030, the impact of higher biomass prices becomes even stronger. By 2050, the use of traditional cookstoves is almost eliminated and the total share of households cooking on solid biomass decreases to 16% (70% of which being modern biomass pellets). This is much lower than the 43% under default biomass prices. As a result, greenhouse gas emissions and especially fuelwood demand will also be lower. However, internalising the negative impacts of solid biomass use in the price results in a fourfold increase in the overall cooking costs.

4.2 Technology and cost implications of various policy and target assumptions

From the scenarios analysis in the previous section it can be concluded that, without specific additional policies, it is very unlikely that universal access to clean cooking technologies will be achieved by 2030. Alternative socio-economic developments, population growth, urbanisation and economic development, have large implications on the choice of cooking fuels and technologies by 2050. In the short term this is not the case. Here, the results of the policy and target scenarios are discussed. All policy and target scenarios are based on the socio-economic assumptions of the SSP2 'middle-of-the-road' scenario. The SSP2 'middle-of-the-road' scenario is hereafter referred to as baseline.

4.2.1 Cooking fuels and technologies

Improving access to gaseous fuels and subsidising cleaner biomass cookstoves are projected to decrease the use of traditional cookstoves, although a large share of the population is still projected to use traditional cookstoves by 2030

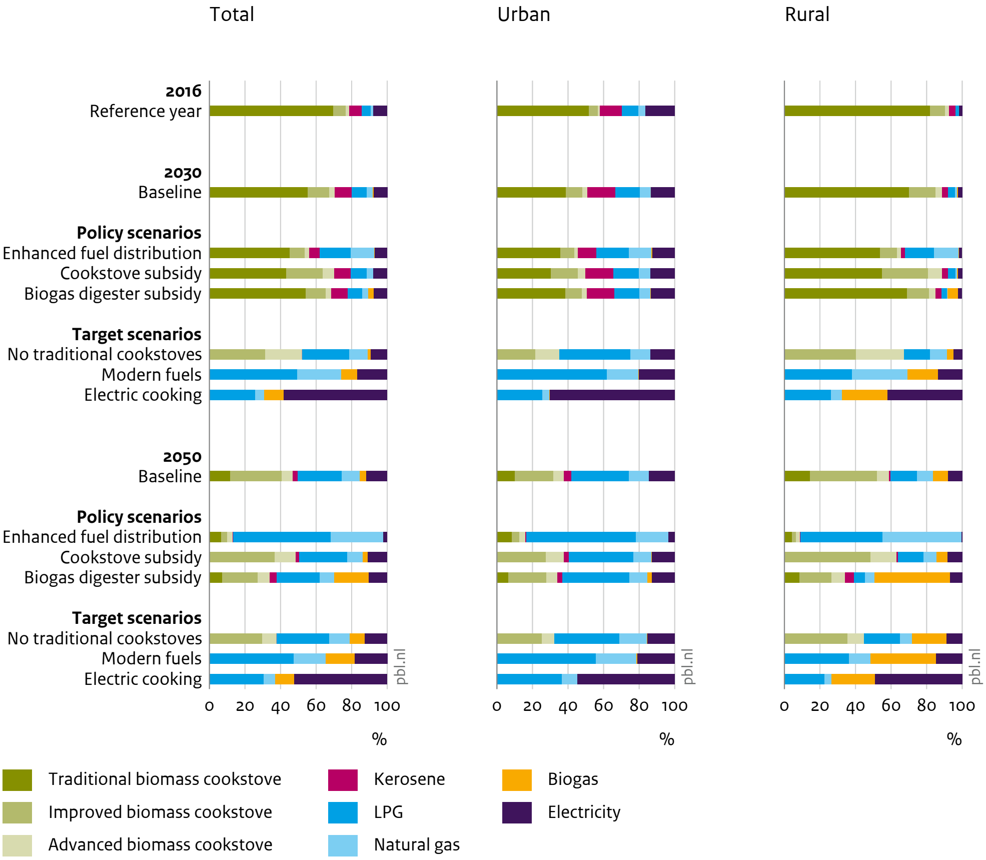
Under the *Enhanced fuel distribution* and *Cookstove subsidy* scenarios, the number of people cooking on traditional cookstoves by 2030 will be about 150 million lower, relative to the baseline scenario (see Figure 7). However, this means that, by 2030, about 580 million people will still be relying on traditional cookstoves. The *biodigester subsidy* scenario shows that the effect of such a subsidy on traditional cookstoves will be negligible by 2030, as it is projected that stoves on biogas will mainly replace improved and advanced cookstoves. By 2050, however, the subsidy will reduce traditional cookstove use, down to 7%, compared to 11% under the baseline scenario. A similar decrease takes place under the *Enhanced fuel distribution* scenario. The use of traditional cookstoves will be practically phased out by 2050, under the *Cookstove subsidy* scenario.

Facilitating affordable access to gaseous fuels shows the largest effect on reducing biomass use, in the longer term, but will also reduce the use of biogas and electricity for cooking

The *Enhanced fuel distribution* scenario shows that facilitating affordable and reliable gaseous fuel supply strongly decreases the use of biomass by 2050. By 2030, after traditional biomass, LPG and natural gas are the most used cooking fuels in this scenario, with 30% of the population cooking on LPG or natural gas. By 2050, the share is projected to increase to 85%. This means that the share of the total population using biomass is decreased to 12% by 2050, compared to 45% in the baseline. At the same time, however, under this scenario, LPG and natural gas will replace the very clean alternatives of electricity and biogas.

Figure 7

Household cooking energy mix in Sub-Saharan Africa



Source: PBL

Phasing out traditional cookstoves or even biomass altogether by 2030 requires a very rapid change from current trends

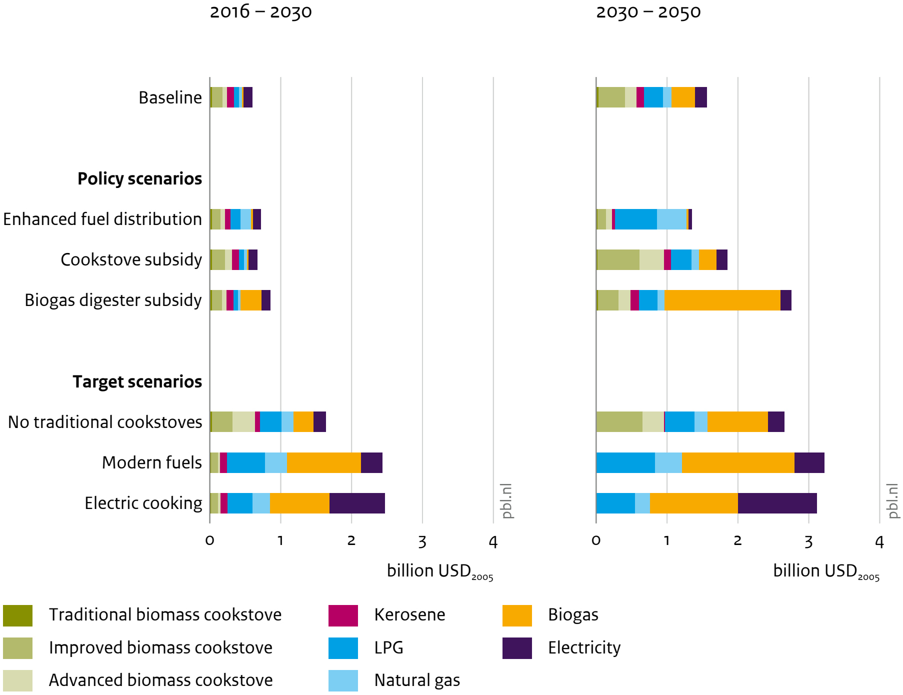
Under the *No traditional cookstoves* scenario, traditional cookstoves and kerosene will be completely phased out by 2030. Under this scenario, by 2030, over half the population will still be using biomass (on either improved or advanced cookstoves) and around a quarter will be using LPG, compared to a respective 66% and 9% under the baseline scenario. By 2050, the shares differ far less from those under to baseline scenario, where the share of the population using traditional cookstoves or kerosene will already be reduced to 15%. The *Modern fuel* scenario is the most ambitious, with all biomass use being phased out by 2030, including the use of advanced cookstoves. The scenario shows a rapid transition, mainly towards liquid and gaseous fuels, and to a lesser extent also towards electric cooking. By 2050, the share of biogas and electricity increases and that of both LPG and natural gas decreases, although more than half of the population will still be using LPG and natural gas, under this scenario. If behavioural change would be assumed for households cooking on electricity (leading to a 50% lower energy demand by those households), the results change considerably, as, in that case, the share of electricity in the cooking energy mix is projected to increase to more than 55% by 2030. After 2030, though the absolute number of people cooking on electricity will increase slightly, the share of electricity in the mix declines as the rapidly growing urban population is provided access largely to LPG and natural gas, which will become cheaper as the supply chain has already been established.

4.2.2 Purchasing costs and fuel expenditure

Under the baseline scenario, total annual purchasing costs are projected to be around USD 600 million over the coming decade, increasing to about USD 1.6 billion, over the 2030–2050 period
The technical lifetime of the various cooking technologies plays an important role in total annual purchasing costs (stoves plus accessories such as cylinders for liquid fuels). Even though the purchasing costs are higher for modern cooking technologies than for biomass cookstoves, they are not always higher as the modern technologies have a 2 to 3 times longer lifetime. Total annual purchasing costs, under the baseline scenario, is USD 600 million over the period 2016–2030, equalling USD 2 per household. Annual purchasing costs will increase over time. In the period 2030–2050, total annual purchasing costs are projected to increase to USD 1.6 billion (USD 3 per household), mainly driven by the shift away from traditional cookstoves. Towards 2030, the largest purchases are made on improved cookstoves, electric stoves and kerosene stoves. After 2030, the shares of LPG and biogas in total purchases will increase.

Of the policy scenarios, the *Biodigester subsidy* scenario is projected to lead to the highest purchasing costs, due to the relatively high costs of biodigesters
Under the *Cookstove subsidy* scenario, purchasing costs related to cookstoves and accessories are projected to be only slightly higher than under the baseline scenario. This can be explained by the fact that traditional cookstoves are mostly replaced with improved cookstoves, which are still relatively cheap, compared to modern cookstoves (see Figure 4). The *Biodigester subsidy* scenario does lead to purchasing costs that are much higher than under the baseline, which can be explained by the relatively high capital costs of biodigesters. Over the 2016–2030 period, about a third of total purchasing costs will be related to the purchase of biodigesters – and, over the 2030–2050 period, this will even be up to 60% – although by 2030 biogas itself will only have a very limited share, and by 2050 this will be only 20%. The *Enhanced fuel distribution* scenario projects, for the short term, a small increase in purchasing costs, compared to under the baseline scenario. For the long term, purchasing costs are projected to be even lower, mainly because the relatively expensive biodigesters will be replaced with LPG and natural gas.

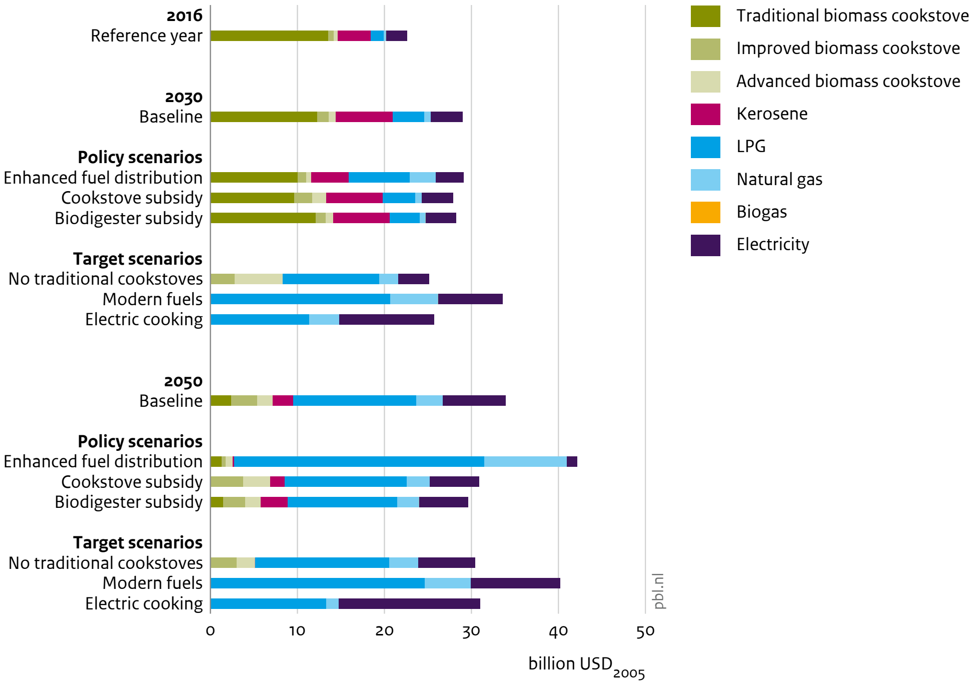
Figure 8
Annual capital expenditure on cookstoves and accessories in Sub-Saharan Africa



Source: PBL

Purchasing costs for phasing out traditional cookstoves, or even biomass altogether, are significantly higher than under the policy scenarios, especially in the short term
Under the *No traditional cookstoves* scenario, total purchasing costs will increase almost threefold compared to under the baseline scenario (USD 1.6 billion annually), over the period 2016–2030. The number of purchases s for practically all alternative cookstove technologies (i.e. improved and advanced cookstoves, LPG, natural gas, biogas and electricity) will be significantly higher than under the baseline scenario. In the longer term, purchasing costs will be about 70% higher than under the baseline, especially due to increases in the purchases of biodigesters, LPG and improved and advanced cookstoves. Under the *Modern fuel* scenarios, purchasing costs will be even four times higher than under the baseline scenario, over the period 2016–2030. This is especially due to a higher number of purchases of biodigesters and electric stoves (the latter mainly under the assumption of behavioural change for households cooking on electricity) and, to a lesser extent, stoves on LPG. Over the longer term, differences will become smaller.

Figure 9
Annual cooking fuel expenditure in Sub-Saharan Africa

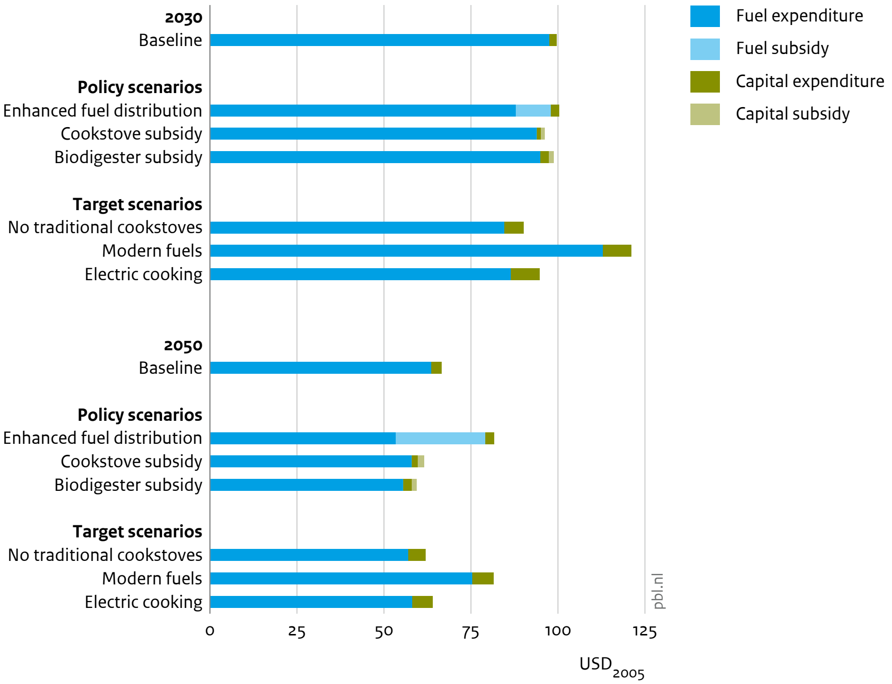


Source: PBL

Projected annual fuel costs will be about USD 30 billion, towards 2030, or lower if a transition towards cleaner biomass cookstoves or biogas takes place

In 2016, annual fuel expenditures were about USD 23 billion, equalling USD 77 per household, with an assumed average cost of USD 0.03 per kilogram for traditional biomass (charcoal and firewood). These costs only include the monetary costs of buying fuels on the market and did not include the opportunity costs of for instance wood collection. Traditional biomass dominated fuel expenditures, with USD 14 billion, followed by kerosene and electricity. Under the baseline scenario, by 2030, total annual fuel costs are projected to increase to around USD 30 billion, equalling USD 100 per household. The policy scenarios show very similar total fuel expenditures for 2030, compared to those under the baseline, which is directly related to a very limited amount of change in the fuels used (see Figure 7). The only major difference is under the *Enhanced fuel distribution* scenario, which shows a much higher expenditure on gaseous fuels, replacing biomass, kerosene, and also electricity. By 2050, the *Enhanced fuel distribution* scenario shows higher expenditures than both the baseline and the other policy

Figure 10
Costs per household in Sub-Saharan Africa



Source: PBL

scenarios, which is caused by the relatively expensive fuels LPG and natural gas replacing biomass and biogas. Fuel expenses are the lowest under the *Biodigester subsidy* scenario, as there are no fuel costs attached to biogas use.

Phasing out traditional cookstove use can lead to lower fuel expenditures

The baseline scenario shows an increase in fuel expenditures on kerosene, gaseous fuels, and electricity, while the total expenditure on biomass remains relatively constant. Phasing out traditional cookstoves and those on kerosene will lead to much lower average annual fuel costs, as more efficient biomass cookstoves are used and because kerosene is expensive. However, if all biomass use is phased out, total fuel costs are projected to increase, as the relatively cheap biomass used in improved and advanced cookstoves is being replaced with more expensive gaseous fuels and electricity.

Under most policy and target scenarios, total annual costs for cooking are lower than under the baseline scenario

Annual fuel expenditures are much higher than annual purchasing costs. This is also shown in Figure 4, which shows both purchasing and annual fuel costs for separate technologies. This is confirmed in Figure 10, which shows the total annual costs under the various scenarios. For the short term, the scenario in which traditional cookstoves are completely phased out shows the lowest total costs, followed by the *Electric cooking*, *Cookstove subsidy* and *Biodigester subsidy* scenarios. All these scenarios show lower annual costs for cooking than the baseline scenario, in both the short and the long term. The scenario in which all biomass is phased out shows higher costs, especially due to relatively high costs for gaseous fuels and electricity. By 2050, the *Enhanced fuel distribution* scenario has by far the highest total costs, compared to the other policy scenarios – almost as high as the scenario in which all biomass is phased out. This is due to the scenario's very high share of gaseous fuels, replacing cheaper options which is a consequence of the fuel distribution enhancement. As a significant share of the costs will be paid for in public money, as this relates to setting up the distribution network, the costs for households are in fact the lowest of all scenarios. This implies that a large sum of public money is needed to enhance fuel distribution (about USD 3 billion by 2030 and USD 13.7 billion by 2050).

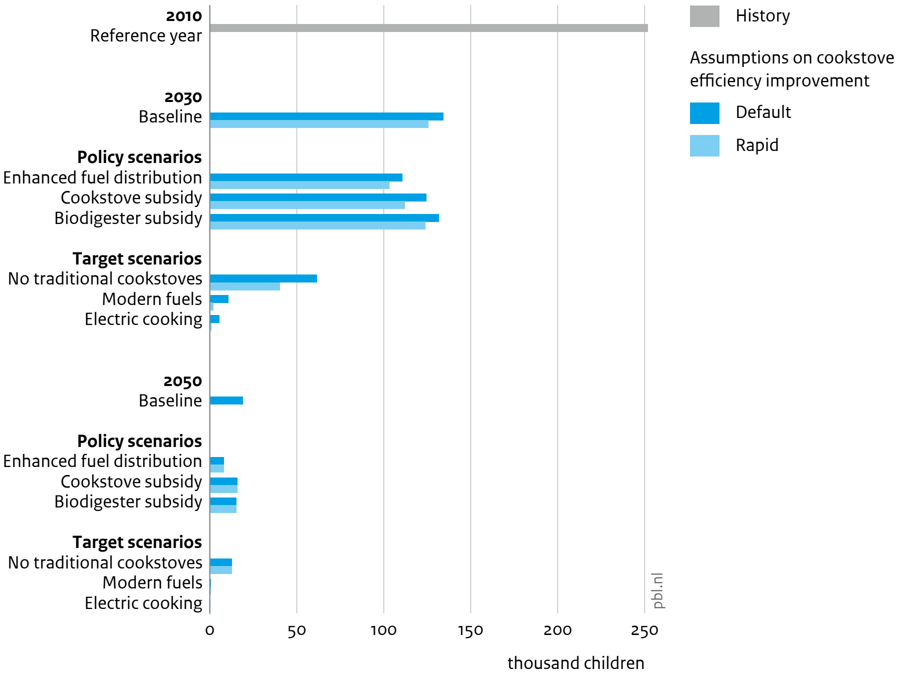
4.3 Implications for human health and the environment

Given the negative side effects of cooking on traditional biomass, a transition towards clean cooking solutions can contribute to achieving several SDGs (GCCA, 2016; Rosenthal et al., 2018). This section discusses the implications of the various policy and target scenarios for human health (SDG3), the risk of deforestation (SDG15) and greenhouse gas emissions (SDG13).

4.3.1 Child mortality

The use of solid fuels and kerosene for cooking and heating produces high levels of household air pollution, most notably carbon monoxide (CO) and fine particle matter emissions ($PM_{2.5}$). Household air pollution is strongly linked to a range of diseases, including acute lower respiratory infections (ALRI), chronic obstructive pulmonary disease (COPD) and lung cancer, with the highest health impacts for women and young children, who spend the most time near stoves. For Sub-Saharan Africa, household air pollution in 2010 is estimated to have been responsible for more than 40% of total ALRI-related deaths in children under the age of 5 (Stanaway et al., 2018). Here, we discuss projections of future deaths related to ALRI attributable to household air pollution, under the various baseline, policy and target scenarios.

Figure 11
Child mortality attributable to household air pollution in Sub-Saharan Africa



Source: PBL

The greatest health benefits are accrued by achieving very low exposures levels

The WHO has set air quality guidelines for $PM_{2.5}$ of 10 µg/m³ and an interim 1 target of 35 µg/m³. (WHO, 2006). The use of open fires or three-stone fires in Sub-Saharan Africa is generally associated with $PM_{2.5}$ concentrations of more than 500 µg/m³, improved cookstoves with more than 110 µg/m³ (improved charcoal stoves are generally less polluting) and advanced cookstoves with more than 35 µg/m³ (World Bank, 2014) (see Table 2). However, as $PM_{2.5}$ exposure-response curves for health impacts, such as ALRI, are exponential (Burnett et al., 2014), the greatest health benefits are accrued by achieving very low exposures levels, well below the interim 1 target (Johnson and Chiang, 2015).

The policy scenarios show only limited impact on child mortality reductions

Under the baseline scenario, attributable child mortality will reduce from around 250,000 in 2010 to 135,000 by 2030, and 125,000 if the implementation in improved and advanced cookstoves goes faster. The policy scenarios only show modest improvements in child mortality by 2030, as the share of biomass-fuelled traditional stoves remains high.

Furthermore, the reduction in the relative health risk when switching from a traditional cookstove to an improved cookstove is only small, even though concentration levels decrease substantially. Only under the *Enhanced fuel distribution* scenario, improvements appear significant (around 20%), as biomass, mostly used to fuel traditional stoves, is partly replaced with LPG and natural gas, with 90% to 99% lower $PM_{2.5}$ emission levels, compared to those from open fires.

Phasing out traditional cookstoves can halve the child mortality that is related to household air pollution, while phasing out the use of biomass could almost eliminate it

The three target scenarios show much higher impacts on child mortality. Currently, improved biomass stoves are in the range of Tier 0–2 emission standards and advanced biomass stoves Tier 2–3. Only well-performing fan gasifiers and, to a lesser extent, natural-draft gasifier stoves approach the emission levels of LPG (World Bank, 2014). If traditional biomass stoves are phased out, attributable mortality by 2030 will be reduced by around 50%, compared to baseline levels, and even by almost 70% if improved and advanced cookstoves already achieve lower pollution levels by 2030. Also phasing out biomass use in combination with improved and advanced cookstoves would reduce attributable mortality by 95% to 99%.

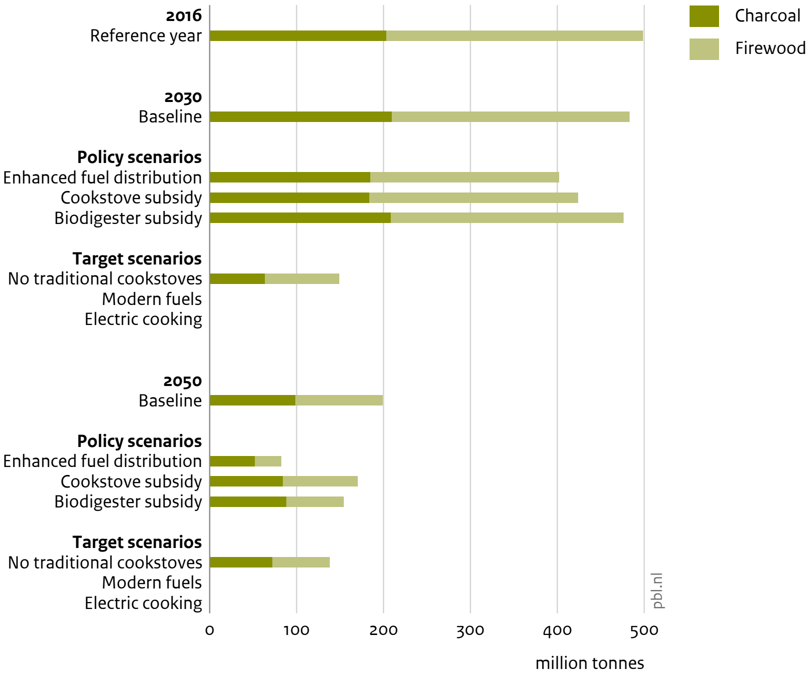
4.3.2 Risk of deforestation

The demand for fuelwood relative to the potential supply generated from natural regrowth is an indicator of the risk of additional deforestation. Here, total wood supply (tonne dry matter/year) is calculated using the IMAGE3.0 model, based on the potential growth of stems and branches in natural vegetation, excluding protected natural area, cropland, grazing land or built-up areas. The wood demand is calculated on the basis of the cooking energy mix in the individual scenarios (Figure 7), a wood-to-charcoal conversion efficiency of 20%, a wood-to-firewood conversion efficiency of 100% and an energy content of energy carriers as provided in Table 7 of the Annex.

By 2030, the demand for fuelwood is projected to decrease slightly under the policy scenarios, compared to baseline developments

In 2016, fuelwood demand in Sub-Saharan Africa was 498 million tonnes (203 million tonnes for charcoal and 295 million tonnes for firewood). Our projections show that, under the baseline scenario, total demand for wood remains relatively constant in the short term and declines to 200 million tonnes by mid century, driven by a shift away from biofuels (also see Figure 7) and efficiency improvements, due to i) shifts to other, more efficient types of cookstoves and fuels, and ii) the development of more efficient versions of existing types of stoves. The policy scenarios show a slight decrease in fuelwood demand by 2030, especially under the *Enhanced fuel distribution and Cookstove subsidy* scenarios, which show a 12%–17% decrease in fuelwood demand compared to the baseline scenario.

Figure 12
Fuelwood demand (charcoal and firewood) in Sub-Saharan Africa

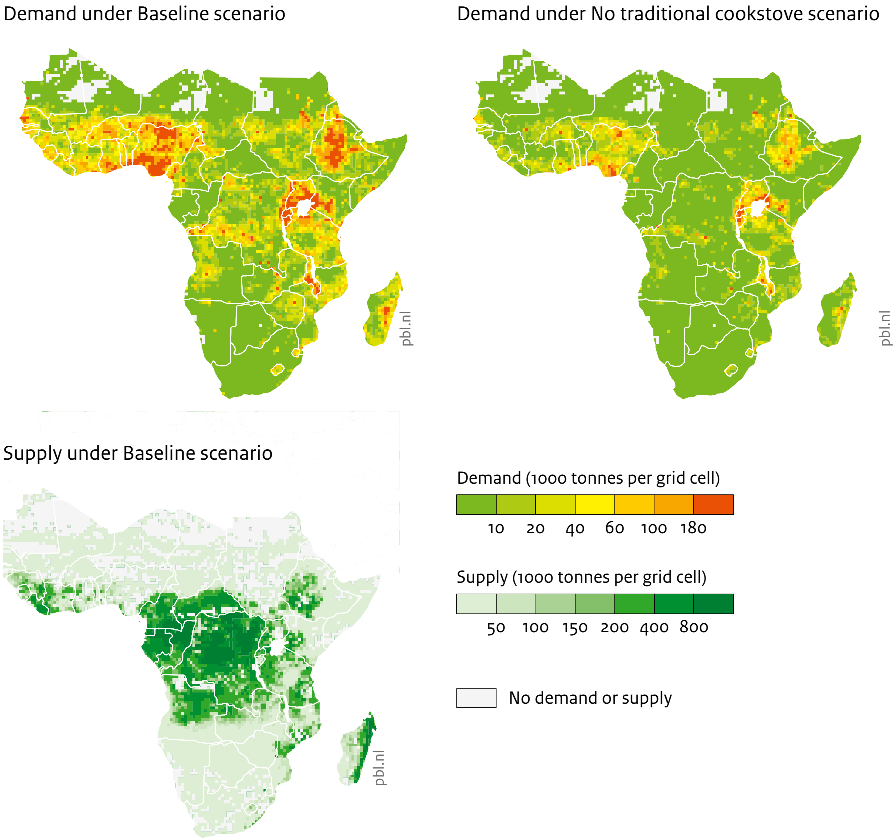


Source: PBL

Phasing out traditional cookstoves leads to a very strong decline in fuelwood demand, already in the short term

As expected, the target scenarios have a much higher impact on fuelwood demand. Phasing out traditional cookstoves implies that, by 2030, fuelwood demand would be 70% lower than the projected demand under the baseline. This, despite the still strong dependence on biomass by 2030, in this scenario, as the shift from traditional to more efficient improved and advanced cookstoves already leads to a much lower demand for wood. By 2050, the reduction in wood demand under the policy scenarios and target scenario, in which traditional cookstoves are phased out, varies from 60% *(Enhanced fuel distribution)* to 15% *(Cookstove subsidy)*. Under the two *Modern fuel* target scenarios, the use of biomass is phased out altogether by 2030 and, therefore, there is no wood demand for cooking at all.

Figure 13
Biomass demand and supply for household cooking, 2030



Source: PBL

For deforestation, harvesting method is more important than absolute fuelwood demand

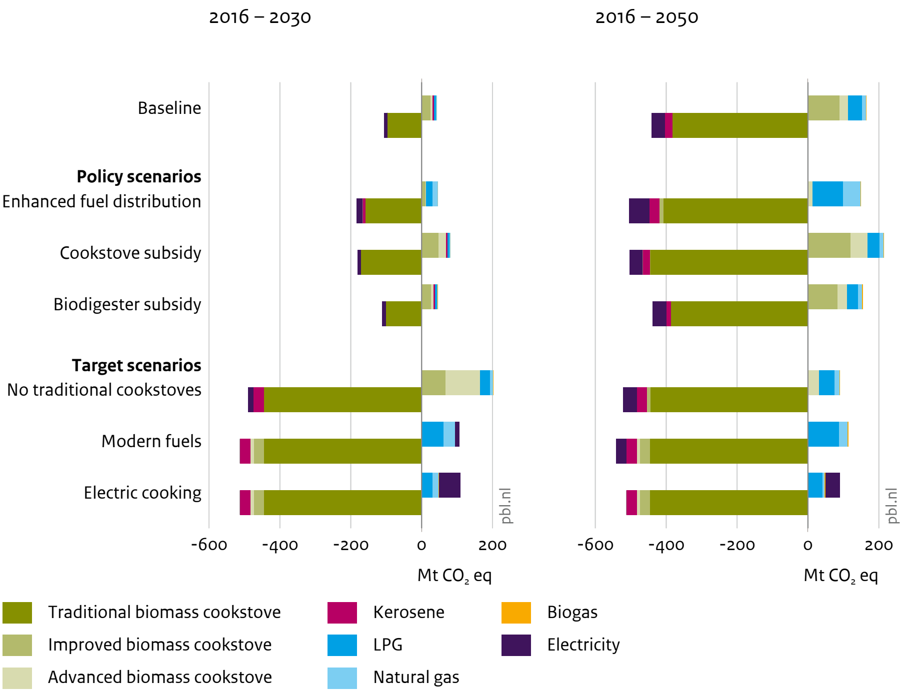
Natural biomass production is estimated at 1340 million tonnes in 2015, 1100 million tonnes by 2030, and 875 million tonnes by 2050. This is much higher than the projected demand under each of the scenarios (Figure 12) and, thus, would not necessarily lead to increased deforestation. These findings are in line with those by Santos et al. (2017), who concluded that the cumulative global supply of net primary production will remain higher than the global demand for biomass. Although we took a more conservative approach, by taking into consideration only the potential growth of stems and branches in natural vegetation instead of all net primary production, we still projected that, for Sub-Saharan Africa as a whole, total supply would be much larger than demand for wood. However, this conclusion only holds under the assumption that biomass is sustainably harvested – which implies that, for deforestation, the harvesting method is more important than the absolute demand for fuelwood.

Biomass demand exceeds supply in several parts of Sub-Saharan Africa, leading to national and/or international trade in fuelwood, and may lead to reduced fuelwood use
The supply of biomass is concentrated in the Congo Basin, the south-western part of western Africa, south-western Ethiopia and parts of Madagascar, while the demand for fuelwood is highly concentrated in high population density settlements in eastern and western Africa (Figure 13). Burundi, Rwanda, and large parts of Uganda and Nigeria face high local biomass deficits because of their low-standing biomass. Similarly, Kenya, Ethiopia, Malawi, Burkina Faso and Ghana also show some local areas of biomass deficits. In these parts, the *No traditional cookstove* scenario leads to much lower local deficits than under any of the other scenarios.

4.3.3 Greenhouse gas emissions
Replacing traditional cookstoves with more efficient biomass or modern-fuel cookstoves may reduce cooking-related greenhouse gas emissions, considerably. Total net CO_2 emissions depend on the way the biomass is harvested. If the woody biomass is not sustainably harvested (i.e. not planting new biomass to replace the harvested biomass or deadwood), burning it will contribute to the amount of CO_2 in the atmosphere (MacCarty et al., 2008). For our projections of biomass-related CO_2 emissions, we assumed 30% unsustainably harvested fuelwood, based on FAO (2017). Burning of wood, agricultural residues, dung, and coal for cooking or heating also contributes to the emission of black carbon (BC) and organic carbon (OC), which are gases that have a strong impact on the climate. For this study, we took CO_2, CH_4, N_2O, BC and OC emissions into account, which are the most important greenhouse gas emissions.

Only under the target scenarios, cooking-related greenhouse gas emissions are drastically reduced, already in the short term
In 2016, total cooking-related greenhouse gas emissions in Sub-Saharan Africa amounted to 600 Mt CO_2 eq, which is almost equal to the total CO_2 emissions of Canada. By far the largest share (75%) came from the burning of solid biomass in traditional cookstoves. Under the baseline scenario, greenhouse gas emissions decline slightly towards 540 Mt CO_2 eq by 2030, despite a projected 35% increase in cooking energy demand related to the expected rapid population growth. The main reason that greenhouse gas emissions decline despite the increase in energy demand is due to a gradual shift to more efficient cookstoves and cooking fuels (see Figure 7). The policy scenarios *Enhanced fuel distribution* and *Cookstove subsidy* result in a 7% to 14% emission reduction by 2030, relative to the *Baseline*, as inefficient traditional cookstoves are replaced with either more efficient gas stoves or more efficient biomass stoves. The *Biodigester subsidy* scenario does not lead to significant net changes in greenhouse gas emissions by 2030, as the subsidy mostly affects cooking technologies, in the long term. The target scenarios show a strong effect on emissions already in the short term, as the inefficient traditional cookstoves are

Figure 14
Change in annual greenhouse gas emissions in Sub-Saharan Africa



Source: PBL

Biomass CO_2 emissions are calculated on the assumption that 30% of the fuelwood is harvested unsustainably, and, for electricity, the average regional greenhouse gas emissions from electricity generation is used.

completely phased out by 2030. The reductions compared to baseline in the target scenarios range from 42% in the *No traditional cookstove* scenario to 64% in the *Modern fuel and Electric cooking* scenarios.

In the long term, greenhouse gas emissions are reduced already strongly, under the baseline scenario
By 2050, under the baseline scenario, greenhouse gas emissions will already be much lower than by 2030 (325 instead of 540 Mt CO_2 eq) due to less fuelwood use. The additional effect of the policy and target scenarios is therefore also smaller, in absolute terms. Notably, of all the policy scenarios, the *Enhanced fuel distribution* scenario shows the largest decline (24%) in emissions compared to the baseline scenario, as additional emissions from gaseous fuels remain well below the amount of avoided emissions from biomass. The other policy scenarios show a very small decline in greenhouse gas emissions, relative to the baseline scenario. All target scenarios show strong reductions of nearly 50%, compared to those under the baseline scenario.

Notes

1 This includes the cost-of-illness of disease (ARI and COPD), cost of emissions (CO_2, N_2O, and CH_4), cost of tree replacement, cost of average daily cooking time, cost of average daily fuel collection time as reported by Jeuland MA and Pattanayak SK. (2012) and amounts to USD 7.8 per month (USD 0.28 per kg for a family of 5).

5 Policy recommendations

Improving access to clean cooking technologies in Sub-Saharan Africa is an important goal for social and economic development and environmental protection. Chapter 4 explores the interactions between affordability of fuels and cookstoves and the availability of fuels, as well as related impacts on human health and the environment, for a range of policy scenarios and target scenarios. Table 4 summarises the results from this quantitative analysis, from which the following policy recommendations can be derived.

Improved and advanced biomass cookstoves could play an important intermediate role in the cooking transition

The ultimate target is to achieve universal access to clean and modern cooking fuels and technologies. However, given the enormity of the challenge, cleaner biomass cookstoves could play an important role in the transition, especially in rural areas, provided that these cookstoves meet the health and environmental requirements, including proper ventilation and sustainably harvested biomass. In that context, several countries in Sub-Saharan Africa already have policies and programmes supporting the diffusion of cleaner biomass cookstoves. These programmes are largely backed by international strategies and programmes, such as the UN's Sustainable Energy for All initiative and the Clean Cooking Alliance. A complete phaseout of traditional biomass use requires long-term investments in markets and infrastructure.

Invest in awareness raising and communication related to the negative side effects of traditional biomass use

For many, primarily rural households, fuelwood collection is free, as, for example, the time spent on collecting it and the negative health impacts of the related household air pollution are not awarded a monetary value. Educating women, who bear the largest burden of traditional cooking, and expanding economic development programmes can improve awareness and thereby increase the opportunity costs of traditional biomass use and stimulate the transition towards clean cooking technologies. Community-based organisations can play a key role in education and awareness-raising with respect to the value proposition and health benefits of clean cooking solutions and stimulate behavioural change among consumers and decision-makers.

Table 4
Summary of model results

Year	Variables / Scenario		Population relying on TCS (%)	Population with access to clean cooking solutions (%)	Average annual purchasing cost per household (USD)	Annual fuel expenditure per household (USD)	ALRI-related child death attributable to household air pollution ('000)	CO_2 eq emissions (Megatonne)	Annual fuelwood demand (million tonnes)
2030	Baseline		50–60	18–22	1.2–2	95–102	134	380–540	451–517
	Policy scenarios	Enhanced fuel distribution system	45	38	2.5	98	111	464	413
		Cookstove subsidy	43	21	1.0	94	125	501	426
		Biodigester subsidy	54	22	1.5	95	132	535	479
	Target scenarios	No traditional cookstoves	0	48	5.5	85	62	313	158
		Modern fuels	0	100	8.2	113	11	195	0
		Electric cooking	0	100	8.3	86	5	198	0
2050	Baseline trends		5–25	38–72	2.6–3.0	64–68	19	205–325	86–295
	Policy scenarios	Enhanced fuel distribution system	7	87	2.5	79	8	219	161
		Cookstove subsidy	0	49	1.7	58	16	234	182
		Biodigester subsidy	7	62	2.6	56	15	229	177
	Target scenarios	No traditional cookstoves	0	62	5.0	57	13	214	152
		Modern fuels	0	100	6.0	75	1	175	0
		Electric cooking	0	100	6.0	58	0.5	181	0

Reduce the purchasing costs of modern stoves and increase the efficiency of cleaner biomass stoves
An important barrier in the transition to clean cooking technologies are the relatively high purchasing costs of new stoves. Reducing the costs of both modern cookstoves and cleaner biomass stoves could significantly improve their diffusion. Furthermore, increased efficiency of improved and advanced biomass cookstoves reduces fuel requirements and thereby the related household costs. Reducing the costs of cookstoves could be achieved indirectly by removing the VAT, import duty, and any other related taxation. In Kenya, for example, these taxes add almost 50% to the retail price of a stove (Lambe et al., 2015). Furthermore, overall cost reductions can be achieved through investment in R&D, capacity building, awareness creation, setting technical standards and providing incentives for the private sector. Efficiency standards can help to reduce overall

fuel requirements and thereby also bring down household expenditures, while quality standards could extend the lifetime of cookstoves, making ownership and maintenance cheaper. In addition, low quality cookstoves may cause negative expectations for the improved cooking technologies, leading to lower adoption rates. Specific attention should be paid to the lowest income segments of the population when designing policies.

Scale up innovative finance models for poor households, as well as financial and technical support for business

Households need access to affordable financial options to pay for the initial costs of cleaner biomass cookstoves, modern fuel cookstoves or biodigesters. One approach is to encourage the development of microfinance that targets both retailers and consumers. Furthermore, the use of smaller cylinders for LPG and natural gas could be promoted. The latter could facilitate access by lowering the initial deposit fee and refilling costs, encouraging more regular consumption of modern fuel, especially in rural areas and low-income urban communities. In the long term, improving access to modern fuels also requires infrastructure and economic development plans. *Donors and financers* could coordinate their efforts, provide strong financial support for innovative business models and new approaches, and provide financing to minimise the investment risk for financing institutes, large-scale producers, clean cooking infrastructures as well as local distributors. The financial barrier is not limited to the purchasing costs alone but also includes the annual operating costs of the stoves. While the additional annual fuel cost of modern fuels is modest, this could be a significant barrier to the transition and sustained use of modern fuel technologies. Therefore, there needs to be additional attention for the annual operating costs of the modern fuel cookstoves, to make sure that people do not go back to the traditional stoves.

Involve a wide array of actors and stakeholders

Local and national governments, research institutes, international aid organisations, financial institutions, and civil society organisations all have a role to play in the transition. In order to be effective, there is a need to coordinate and strengthen their efforts in capacity-building, awareness creation, facilitating dialogue and scaling up finance to enable access for both retailers and consumers. Donor organisations could engage with governments and the private sector to provide technical assistance for institutional capacity building and the establishment of technical standards for cookstoves, financing research and development of efficient technologies that benefit human health and the environment. Public–private partnerships have become increasingly popular in global and Dutch development cooperation. Meeting their full potential requires that, in the design of partnership agreements, specific attention is paid to the allocation of risks and responsibilities, and that the interests of the various partners are explicitly defined, negotiated and aligned (Bouma and Berkhout, 2015).

To achieve its target on renewable energy access, Dutch development cooperation could focus on stimulating the use of sustainable biomass, biogas and electricity

Our results show that LPG and natural gas could play a large role in the transition towards universal access to clean cooking technologies, due to their relatively low costs compared to other clean technologies and considerable health and environmental benefits compared to traditional biomass use. Renewable energy technologies also have an important role to play, including the use of advanced biomass stoves in the short to medium term, and biogas and electricity (especially if the electricity is generated from renewable resources) for the longer term. In that context, Dutch development cooperation could focus on stimulating the adoption of advanced cookstoves, and those on biogas and electricity. Overall, this includes awareness creation on the benefits of clean cooking. With respect to advanced biomass use, this includes stimulating sustainable biomass production through forest plantations, sustainable forest management and more sustainable charcoal production. For biogas, this includes supporting R&D for biodigesters to reduce their price and stimulate access to financing for both households and manufacturers. Finally, electric cooking requires access to electricity, including off-grid electricity generation for rural communities (Lucas et al., 2017), and access to financing for producers and consumers.

Integrate efforts to achieve universal access to clean cooking solutions into policies on broader poverty alleviation and economic development

A transition towards clean cooking solutions can contribute to achieving a range of SDGs. This study discusses significant synergistic effects with improving child health (SDG3), reducing greenhouse gas emissions (SDG13) and reducing deforestation, land degradation and biodiversity loss (SDG15). However, there are also many indirect synergies with SDG targets that require attention in Sub-Saharan Africa, such as with reducing poverty (SDG1), promoting quality education for all (SDG4), promoting gender equality (SDG5), enhancing productivity and inclusive economic growth (SDG8), and making cities and communities sustainable (SDG11) (GCCA, 2016; Rosenthal et al., 2018). Coordinating initiatives and policies that are aimed to provide clean cooking solutions to be in line with policies and programmes on rural education, human health, universal access to electricity, climate change mitigation, environmental programmes and industrialisation. This could increase synergies between the programmes, facilitate the transition and bring the SDGs closer to realisation.

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Annex

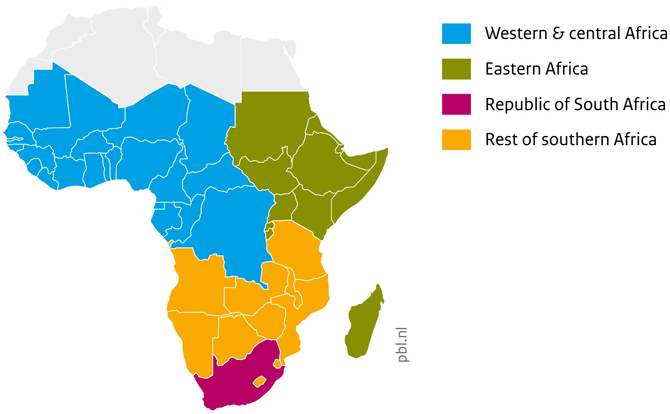
1. Regional groupings

In our model, Sub-Saharan Africa is divided into four sub-regions, namely western & central Africa, eastern Africa, the rest of southern Africa and the Republic of South Africa. The regional groupings and the list of the countries within the regions are shown in Table 5 and Figure 15.

Table 5
List of countries in the four regions of Sub-Saharan Africa

Regions				
Western Africa		**Eastern Africa**	**Rest of southern Africa**	**South Africa**
1. Benin	2. Burkina Faso	1. Burundi	1. Angola	1. South Africa
3. Cameroon	4. Cape Verde	2. Comoros	2. Botswana	
5. CAR	6. Chad	3. Djibouti	3. Lesotho	
7. Congo Dem Rep	8. Congo Rep	4. Eritrea	4. Malawi	
9. Cote d'Ivoire	10. Equatorial Guinea	5. Ethiopia	5. Mozambique	
11. Gabon	12. Gambia	6. Kenya	6. Namibia	
13. Ghana	14. Guinea-Bissau	7. Madagascar	7. Swaziland	
15. Liberia	16. Mali	8. Mauritius	8. Tanzania	
17. Mauritania	18. Niger	9. Reunion	9. Zambia	
19. Nigeria	20. Sao Tome & Principe	10. Rwanda	10. Zimbabwe	
21. Senegal	22. Sierra Leone	11. Seychelles		
23. St. Helena	24. Togo	12. Somalia		
		13. Sudan		
		14. Uganda		

Figure 15
Regional grouping of African countries



Source: PBL

2. Stove and fuel characteristics

In the analysis, the model takes both traditional and modern fuels into consideration. The stove and fuel prices reflect the availability and accessibility of the technology and/or fuel. The biomass prices also reflect the opportunity cost of time spent on fuel collection and the time spent on cooking. The lifetime of the technology affects the depreciation and stock of the stove. The total cost of switching fuel type and/or technology includes the annual costs of acquiring the cookstove (and cylinders, when necessary) as well as the fuel for cooking. The literature gives a range of values for cookstoves cost (given as 'stove price literature' in Table 6) and fuel prices (given as 'model fuel price' in Table 6). The model uses average prices for cookstoves as given under the column model stove prices. We have implemented homogeneous value for biomass fuel prices, while the price of other fuels differs per region in Sub-Saharan Africa.

Table 6

Characteristics of cooking technology and fuel combinations

Fuel	Definition	Technology	Cookstove lifetime (Years)	Purchasing costs	Conversion efficiency	Model fuel price ($/GJ)	Daily hours of cooking[1]
Traditional biomass (firewood, agricultural residues, animal dung)	Refers to all organic matter derived from living or recently living organisms, plant and animal-based. The raw biomass is burned directly in a stove	Traditional cookstove	2	USD 0.50	12%	2.00	2–4
		Improved cookstove	3	USD 25 in 2015, average annual decline of 2%	30%	2.00	1.9–3.8
Modern biomass (briquettes, pellets)	Refers to all organic matter derived from living or recently living organisms, plant and animal-based. The raw biomass is processed into compact, evenly sized pieces.	Advanced cookstove	5	USD 65 in 2015, average annual decline of 2%	40%	8.20	1.5–3
Charcoal	Charcoal is the lightweight black carbon and ash residue hydrocarbon produced by removing water and other volatile constituents from animal and vegetation substances, which allows it to burn to a higher temperature	improved cookstove	3	USD 25	30%	2.00	1.5–3
		Advanced cookstove	5	USD 45	40%	2.00	1.5–3
Coal	A solid combustible substance formed by the partial decomposition of vegetable matter without free access of air and under the influence of moisture and often increased pressure and temperature that is widely used as a natural fuel	improved coal cookstove	4	USD 25	15%	2.20–3.59	1.5–3

Kerosene	A liquid product of crude oil, natural gas and/or coal that is widely used in urban households for cooking, heating and lighting. It is also referred to as paraffin in some countries.	Kerosene stove	4	USD 20	35%	13.21–15.67	1–3
LPG	A by-product of natural gas and crude oil refining which consists of a mixture of propane and butane for standard heating and cooking uses.	Double burner	10	USD 35 in 2015, average annual decline of 1%	50%	13.12–15.67	1–3
		Single burner	10	USD 55 in 2015, average annual decline of 1%	50%	13.12–15.67	1–3
Natural gas	Natural gas is a fossil fuel used as a source of energy for heating, cooking, and electricity generation. Natural gas consists mainly of methane	Gas stove	10	USD 55 in 2015, average annual decline of 1%	50%	8.73–13.34	1–3
Biogas	A methane-rich gas produced by anaerobic (without air) digestion of from organic waste (e.g. animal dung, agricultural residues and food waste).	Gas stove & digester	20 (for digester)	USD 550 in 2015, average annual decline of 2%	40%	0	1–3
Electricity	Electricity generated from coal, natural gas, hydropower, nuclear, oil, solar, wind, and biomass. It is clean and efficient at point of use, though overall lifecycle cleanliness and efficiency is dependent on the source.	Electric/ Induction	10	USD 70 in 2015, average annual decline of 2%	75% in 2016 reaches 90% by 2030	24.92–45.02	1.2–2.4

Source: Bruce et al., 2017; Daioglou, 2010; IEA, 2014a; IEA, 2014b; Jeuland and Soo, 2016; Jeuland and Pattanayak, 2012; Kaygusuz, 2011

Table 7

Energy carriers

Fuel	Energy content	CO_2 emissions in 2016 (kg/GJ)	CH_4 as CO_2 eq (kg/GJ)	N_2O as CO_2 eq (kg/GJ)	BC as CO_2 eq (kg/GJ)	CO as CO_2 eq (kg/GJ)
Firewood, air-dried (15%) moisture)	16 MJ/kg	0–112[1]	21.60	1.16	96.74	-14.17
Charcoal	30 MJ/kg	121	14.40	0.29	96.74	-14.17
Kerosene	43 MJ/kg	72	0.22	0.17	55.19	-0.79
Liquefied Petroleum Gas (LPG)	45.5 MJ/kg	63	0.07	0.03	3.92	-0.42
(Liquefied) natural gas (LNG)	38 MJ/ m^3	56	0.36	0.03	0.00	-0.00
Biogas	22.8 MJ/m^3	0	0.72	0.17	3.91	-0.42
Electricity	3.6 MJ/kWh	70–250[2] kg/GWh2				

Source: IPCC, 2006, 2014

1 It is assumed that the net emission at the point of combustion is zero if fuelwood is sustainably harvested, FAO (2017) estimates that 27% to 34% of fuelwood harvesting in tropical regions is unsustainable.

2 The range shows the carbon intensity of the grid in the regions in 2016.

3 We have used the GWP-100 assigned for CO_2=1, CH_4=25, N_2O=298, BC=900, and OC=-46 to calculate CO_2 eq, we have not included other pollutants due to large uncertainties associated with their role in global warming or because they have not agreed on the Global Warming Potential.

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