npj | clean energy

Article

https://doi.org/10.1038/s44406-025-00017-1

Integrated geospatial modelling for the achievement of universal energy access in Kenya

Babak Khavari[1], Andreas Sahlberg[1], Camilo Ramirez[1], Sarah Odera[2], Elsie Onsongo[3], Kevin Nayema[3], Victor Otieno[4], Douglas Ronoh[4], Anobha Gurung[5] & Francesco Fuso Nerini[1,6] ✉

Access to clean cooking and electricity are both targets of Sustainable Development Goal 7, with uneven progress. Peer-reviewed literature and policy documents have called for more integrated planning efforts accounting for both targets simultaneously. Here, we soft-link for the first time a geospatial electrification tool (OnSSET) with a geospatial clean cooking tool (OnStove) to allow for integrated planning in a case-study of Kenya. Integrated planning in this case refers to when electricity and clean cooking access are modeled for together. In 2021, 77% of Kenyans had access to electricity, but only 28% to clean cooking. The government has targeted universal electricity and clean cooking access by 2026 and 2028 respectively, and the country has considerable potential for electric cooking. Our results show how incorporating cooking demand in the electricity sector, favors centralized options as these benefit from economies of scale. On the clean cooking side, 77% of the population would have the highest net-benefit from adopting an electric option in the absence of integrated planning and these shares increase to between 85 and 91% in the integrated case. We find that an integrated approach is important for understanding the best way forward towards the achievement of SDG 7.

Sustainable Development Goal 7 (SDG 7) aims to *"ensure access to affordable, reliable, sustainable and modern energy for all by 2030"*. While this goal has been recognized as linked to the achievement of all SDGs[1,2], its achievement has remained elusive across the targets, including the one for universal energy access[3,4]. SDG 7 includes targets for both access to electricity and clean cooking. However, there is a large discrepancy between the outlooks of these two targets. As of 2024, 730 million people lacked access to electricity, and nearly 2 billion people lacked access to clean cooking[5]. The access deficit is most pronounced in Sub-Saharan Africa (SSA) where merely around 50 and 18% of the population had access to electricity and clean cooking, respectively in 2024[5].

Access to electricity and clean cooking are inherently interlinked. Electricity is considered a clean cooking fuel and consequently as electricity access increases so does the potential of clean cooking[6]. On the other hand, electric cooking being used sparsely in many regions of the world currently means that the electricity sector risks becoming inadequate as electric cooking loads increase[7]. A way to combat this is integrated energy access planning, where clean cooking and electricity access are planned simultaneously. This has also been highlighted and increasingly sought by both policy and scientific literature, with evidence of those benefits from e-cooking literature[7–10], energy systems approaches[11,12], and technology solutions studies[13].

The case of electric cooking is becoming increasingly strengthened as off-grid electrification systems and electric cooking appliances are simultaneously becoming cheaper and more efficient[9,10]. These developments could potentially relax the affordability and supply barriers highlighted in the literature. Off-grid systems becoming a more viable option for electric cooking also opens for integrated planning, in which both electricity and clean cooking access are planned for together. Lombardi et al. assess the techno-economic potential for PV micro-grids to provide both electricity and clean cooking access[13]. They show that existing residential load profiles change by incorporating electric cooking and that this leads to higher investments for electrification, but a comparable Levelized Cost of Electricity (LCoE). They argue that the costs of cooking a meal with electricity is competitive with LPG[13]. Sánchez-Jacob et al. use the Reference Electrification Model (REM) to assess the viability of electric cooking. They reach the

[1]Division of Energy Systems and KTH Climate Action Centre, KTH Royal Institute of Technology, Stockholm, Sweden. [2]Strathmore Energy Research Centre, Strathmore University, Nairobi, Kenya. [3]Nuvoni Centre for Innovation Research, Centenary House, Nairobi, Kenya. [4]World Resources Institute, Washington, DC, USA. [5]Clean Cooking Alliance, Washington, DC, USA. [6]Environmental Change Institute, University of Oxford, Oxford, UK. ✉e-mail: ffn@kth.se

conclusion that electric cooking is cost-competitive with other types of fuels (clean and traditional) when using the grid[14]. Similarly, Lee et al. use REM to compare the cost of electric cooking with the costs of cooking with LPG. They suggest that electric cooking is already cost-competitive for a large portion of the population at the current electricity cost, and that as more people start cooking with electricity a feed-back loop leads to a decreasing per-unit cost of electricity, further increasing its competitiveness[15]. The aforementioned studies are mostly cost comparisons and do not account for different cooking solutions having different health, time and environmental benefits[13–15].

Here, we soft-link the Open Source Spatial Electrification Tool (OnSSET) and the clean cooking tool OnStove to develop integrated energy access scenarios. OnSSET is a geospatial electrification tool that determines the costs of electrifying settlements and selects, between a number of off-grid options and the grid, the technology-configuration which minimizes the LCoE. OnStove is a geospatial clean cooking tool which calculates and compares the costs and benefits of different cook stoves and selects the stove with the highest net-benefit (total benefits minus total costs). The integrated approach presented here enables a deeper assessment of how increased electricity and clean cooking access interact beyond a pure cost comparison. We apply this integrated approach on a case study of Kenya.

Kenya is lauded for its growth in electricity access over the past decades. Between the years of 2000 and 2021, the electricity access rates has increased from 15 to 77%[5]. This growth has been the result of initiatives such as grid densification undertaken through the Last Mile Connectivity Project, providing a grid connection subsidy to households located within 600 meters of transformers, and the Global Partnership for Output Based Aid, seeking to electrify informal settlements[16]. In 2018, Kenya launched the Kenya National Electrification Strategy to address barriers that still existed in the sector, among them, high costs of connecting households and supplying electricity to rural and peri-urban areas, lack of incentives to attract private sector investors, and lack of appropriate technical standards, among others. This strategy also sought to identify areas suitable for off-grid electrification based on low electricity demand coupled with sparse population densities. This plan led to the Kenya Off-grid Solar Access Project, providing subsidies for off-grid electrification using mini-grids and solar-home systems in 14 underserved counties[17]. At the time of writing around 23 million people connect to some form of off-grid solar system in the country[5]. Beyond this, a small share of the population are connected to mini-grids[5].

Progress towards universal clean cooking is slower. The Kenya Household Cooking Sector Study from 2019 indicates that 80% of the population rely on traditional fuels for cooking to some extent. There are considerable discrepancies between urban and rural areas, as 94% of the rural population relies on traditional fuels, whereas the same share for the urban population is 53%[18]. The national share of three-stone open fire stoves have decreased from 76 to 58% between 1999 and 2019, but this still constitutes an increase of around 2.5 million households in absolute numbers due to population growth[18]. The stove shares collected by Nuvoni Centre for Innovation Research in their clean cooking survey indicates a clean cooking access rate of 28% nationally (for comparison, 2023 year's Tracking SDG 7 report indicates 24% access to clean cooking as of 2021).

Developments in Kenya's energy sector were realized through the ratification of the Energy Acts of 2006 and 2019. Notably, the Energy Act 2019 mandates the development of energy plans at the county level. These sub-national plans together with national energy plans such as the Least Cost Power Development Plan co-created by state agencies such as Kenya Power, Kenya Electricity Generating Company and Kenya Electricity Transmission Company are ratified by the National Government to form the Integrated National Energy Plan (INEP)[19]. These two documents regulate and provide guidelines on energy planning. It is worth noting that for the first time, according to the draft INEP framework, national and subnational governments are mandated to plan for clean cooking. The goal of these plans is to fast-track the transition to clean cooking with a goal of universal access by 2028.

Results

The impacts of an integrated approach

Integrated planning can be assumed to impact both the least-cost technology mix indicated by OnSSET and the optimal stove-mix in OnStove (hereafter, "optimal" refers to the stove-mix with the highest net-benefit). Here, we use the scenario prioritizing based on highest population density and compare an integrated approach to the non-integrated one. Following the workflow in methods, Fig. 7, equilibrium is reached after six iterations. After the first iteration, OnStove identifies electric cooking as the choice with the maximum benefits for 54.8 million people across Kenya in 2028. This number decreases and eventually stabilizes around 53.0 million people at equilibrium.

The new connections to different categories of electrification technologies are explored to assess the impacts of integrated planning for the electricity access scenarios. In the scenario without integration, the share of new grid connections is 62%, 9% for mini-grids and 29% for stand-alone PV. With an integrated approach, grid rises to 72% of the new connections, while mini-grids rise to 16% and stand-alone decrease to 12% at equilibrium. The move away from stand-alone with growing demands is expected as the other options benefit from economies of scale[20–22]. Further insights can be gained by exploring the spatial distribution of technologies (Fig. 1). In both cases, grid connections dominate in the southern parts of the country, where population density is high. In the northern parts, some of the settlements that would otherwise have used stand-alone systems, would instead use either mini-grids or grid connections when an integrated approach is used. This is due to the demand increasing enough to economically justify grid extensions with cooking loads. In both cases some settlements with existing mini-grids would be connected to the centralized grid by the end of the analysis. This indicates that electricity consumption in these settlements is large enough for these mini-grids to be integrated into the existing main-grid.

Total investments needed for 100% electrification also differs between the scenarios. Without electric cooking, 3.3 billion USD is needed between 2022 and 2026, 79% of this for the grid, 17% for stand-alone systems and 4% for mini-grids. The investment cost at equilibrium increases to 4.5 billion USD (88% grid, 3% stand-alone, and 9% mini-grids). Furthermore, the LCoE changes with cooking demand (Fig. 2). Larger demand decreases the LCoE, especially in the north, where the relative wealth (RW) is the lowest. This is also highlighted in the cumulative distribution functions (CDF) in Fig. 2, which shows the biggest gaps between the LCoE-curves for the lower quintiles.

Figure 3 shows OnStove results without integration. Four stoves maximize net-benefits in the end year (panel a), EPC (44% of the total population), electric hobs (33%), LPG (23%), and biogas (<1%). No other stoves are selected here. In the northern regions of the country, LPG is selected for the majority of the population due to lower electricity access rates. In the southern parts of the country, electrical options are more prevalent, especially around the major cities (panel b). Panel c) shows where each stove is selected in relation to RW. LPG stoves and EPCs are important mainly in the lower quintiles, while electric hobs are especially important in the higher quintiles. The reason for this is due to the areas with high population densities having higher RW and electrical hobs are favored in the beginning of the analysis due to their longer technical life and lower investment costs. This indicates that EPCs and LPG could potentially benefit from subsidies as the population in the lower quintiles may otherwise have difficulties adopting these appliances. With regards to net-benefits, all stoves' benefits outweigh their costs (panel d). Across all stoves, health benefits due to lower $PM_{2.5}$-concentrations compared to the current stoves are the largest benefit. For biogas stoves and the electric options, there are fuel savings. In the case of biogas this is because fuel is assumed to be collected, leading to zero fuel costs. For electric options, it can be attributed high efficiencies and high LPG costs (and LPG's significance in the current stove mix across Kenya).

With integration, the results change (Fig. 4). 63% of the population would get the highest net-benefit with EPCs, 25% with electrical hobs, 12%

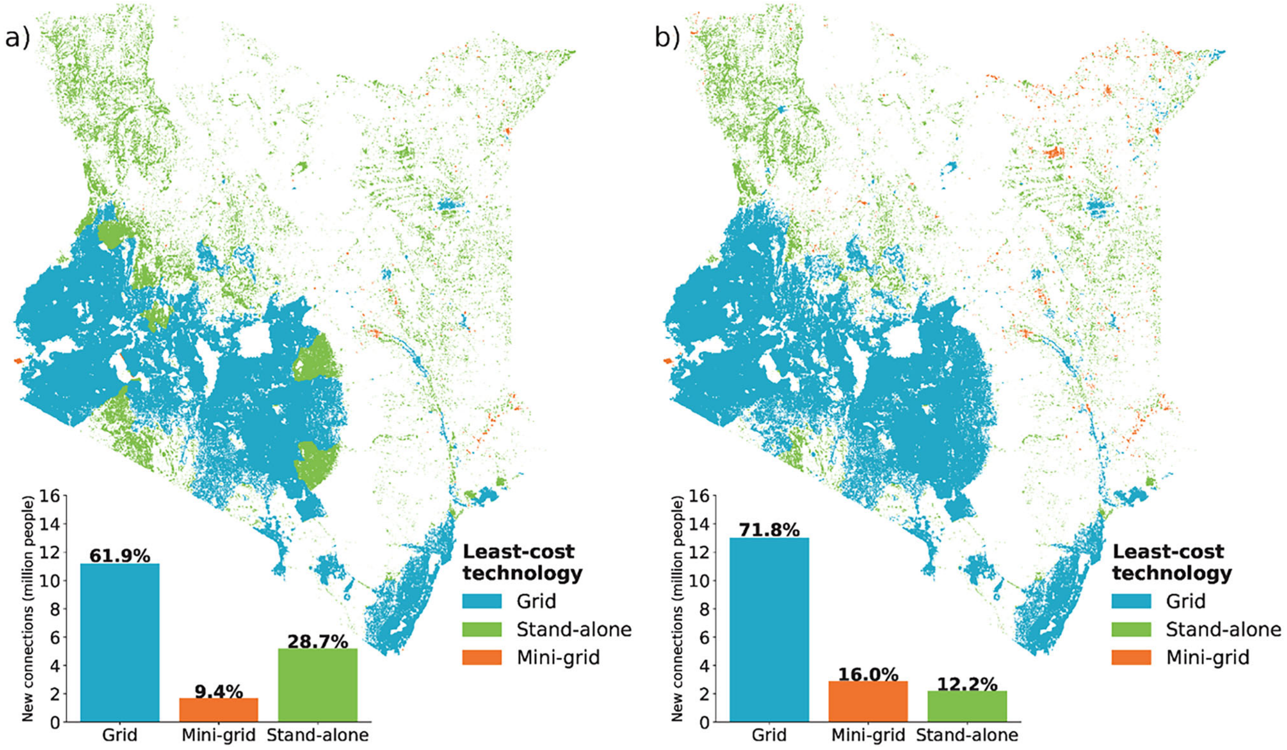

Fig. 1 | Spatial distribution of different electrification technologies in the scenarios, as well as the absolute number and percentage of new connections to each technology-category. The left panel (**a**) shows the scenario with no cooking demand and the right panel (**b**) shows the integrated scenario at equilibrium when prioritizing clean cooking access based on population density.

with LPG, and <1% with biogas (panel a). Comparing Fig. 4b with Fig. 1b shows how electric options take over in an absolute majority of cases where grid and mini-grids are selected in OnSSET. With integration, the cost of adding necessary electricity capacity is included in the calculation of the LCoE in OnSSET. This in turn increases the fuel cost of electricity and favors EPCs as they are more efficient than electrical hobs. This is evident by comparing electrical options in (d) from Fig. 4 to (d) from Fig. 3. Figure 4d indicates a smaller fuel benefit per household due to higher costs of electricity.

Across the different benefit categories included in OnStove, there are no significant changes with integration. Regardless of integration or not around 46,000 deaths are avoided by the transition. Costs avoided due to reduced morbidity and mortality increase from 10.1 to 10.2 billion USD with integrated planning. Time saved per day and household amounts to 1.5 and 1.6 h without and with integration, respectively, driven mainly by the fact that the electric options included have lower cooking times. Contrary to what might be expected, the integrated scenario increases the total emissions by 5 million tonne CO_2- eq. during the modeling period. As EPCs have higher efficiencies and the electricity mix of Kenya is relatively clean, this indicates that EPCs come later during the modeling period. If the modeling period is expanded beyond 2028, we would likely see the emission benefits of the integrated scenario catching up and eventually surpassing the non-soft-linked scenario.

Effects of prioritizing differently

Figure 5 shows the main OnStove and OnSSET results while prioritizing based on highest current costs and highest current drawbacks during the integration. When prioritizing based on highest current costs, electric cooking starts as the optimal solutions for 53.8 million people and drops to 51.8 million at equilibrium (fifth round). Prioritization based on highest current drawbacks leads to equilibrium after three rounds and population cooking with electricity drops from 56.1 to 55.5 million.

The effect of prioritization in OnStove also translates to OnSSET (Fig. 6a, b). The LCoE produced by OnSSET with the three different approaches to prioritizing clean cooking is similar across all wealth quintiles. This indicates that the difference in results can be attributed mainly to the order in which settlements receive clean cooking. The OnSSET scenarios developed here assume that access is first densified (the population living in partly electrified settlements are electrified first) and then based on lowest investment cost per capita. Furthermore, OnStove does not allow for a reinvestment in a cell until the stove's technical life has reached its end. This means that if a non-electric stove is favored due to a cell lacking access to electricity, the population cannot switch at a later stage solely because they now have access to electricity. See Fig. 1 in the supplementary material for which cells receive clean cooking access in which year and their electricity status with the different methods of prioritization.

The benefits over the modeling period for the scenario prioritizing based on the highest current costs are comparable to the soft-linked scenario with urban prioritization. For the scenario prioritizing based on the highest current drawbacks, the number of deaths and health costs avoided increase to 48,000 and 10.7 billion US,D respectively. Time saved increases to 1.7 h per household and day, while emissions avoided is comparable to the other integrated scenarios.

The role of EPCs

Across all scenarios, EPCs are selected, and with an integrated approach their share increases. Previously, it has been indicated that EPCs, while being highly efficient and clean, are sometimes incompatible with local dishes and cooking practices[23]. Therefore, we develop an integrated scenario using the urban prioritization but without EPCs, to mimic a case where other stoves are favored.

This scenario reaches equilibrium after four iterations. The changes in OnSSET between this scenario and the one with EPCs are negligible. OnStove indicates that the removal of EPCs do not increase the competitiveness of LPG or biogas stoves considerably (Fig. 6). Instead, the share of electric hobs increase, as does induction hobs (a, b). When EPCs are included, induction hobs are never selected due to them being outcompeted

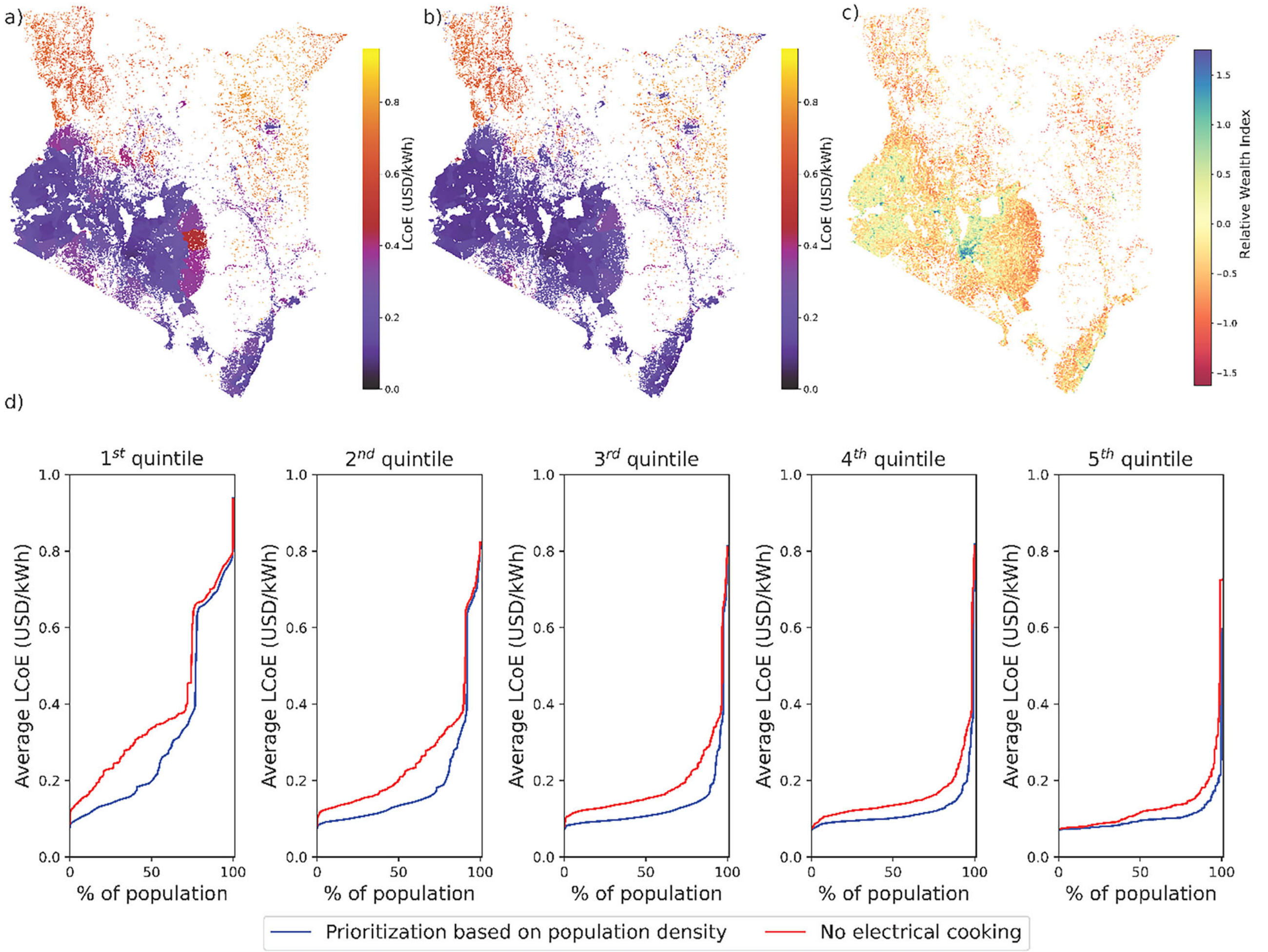

Fig. 2 | Impact on LCoE from including electric cooking. **a** spatial distribution of LCoE without electric cooking, **b** spatial distribution of LCoE at equilibrium using prioritization based on population density, **c** spatial distribution of relative wealth and **d** CDFs for each wealth quintile, highlighting the difference between the LCoE in each quintile with (blue lines) and without (red lines) electric cooking.

by the EPCs' higher efficiencies and the electric hobs' lower investment costs. The fuel cost of electric hobs is positive, indicating that the stove is selected mainly in areas where the current fuel cost is high (c). Figure 6d indicates that electric hobs are selected mainly in the upper quintiles, while induction hobs are selected mainly in the lower ones.

The overall benefits and costs of this scenario are comparable to the case of having EPCs, as induction hobs and EPCs change only slightly in terms of benefits. During the modeling period, the scenario without EPCs has an investment cost of 432 million USD, while the one with EPCs included and urban prioritization increases investments to 445 million USD. The investment costs of electric stoves in this scenario, just like in the case of the other integrated scenarios, includes only the cost of investing directly in new stoves. The fuel cost of the scenario without EPCs is around 50 million USD higher during the modeling period.

Discussion

Connecting electricity and clean cooking planning is of utmost importance, and has co-benefits in both sectors. However, to date, geospatial analytical tools to connect the two beyond cost estimates were missing. In this study, we have developed and implemented a workflow for soft-linking a spatial least-cost electrification tool, OnSSET, with the geospatial clean cooking tool, OnStove, to facilitate integrated energy access planning. To our knowledge, this is the first time this type of soft-link is carried out, accounting for both costs and benefits of an integrated energy access assessment. This allows for planning towards both indicators included in SDG 7.1. We have also expanded OnStove to calculate the costs and benefits year-by-year and enable the users of the tool to select three different approaches to increasing clean cooking access, prioritizing based on either population density, highest current costs, or lowest current benefits.

We show that integrated planning in Kenya could increase the perceived competitiveness of electric cooking. This highlights the importance of exploring different ways of overcoming the barriers mentioned in the literature with regards to uptake of electric cooking, whether it is supply irregularities and unavailability, affordability constraints or perceptions regarding safety. For example, the Energy and Petroleum Regulatory Authority estimates households in Kenya to experience blackouts totaling 25 full days during an average year[24]. Cooking, which needs to be done every day and in many cases more than once a day, requires reliable supply to enhance consumer confidence. With integrated planning some problems arising from planning for increased electricity and clean cooking access in silos can be avoided. For example, Nepal with its high electricity access rate is now looking to adopt a higher share of electric cooking to relax the import-reliance on LPG. However, due to the wiring and transformers currently used, there is a need for considerable upgrades and rewiring of the existing system[25].

Not considering electric cooking demand in electricity models may provide inaccurate investment insights. An integrated approach increases the costs needed for the electricity sector from 3.3 to between 4.1 and 4.8 billion USD depending on which prioritization is used. The increase in cost is driven by a larger share of centralized options and higher demands.

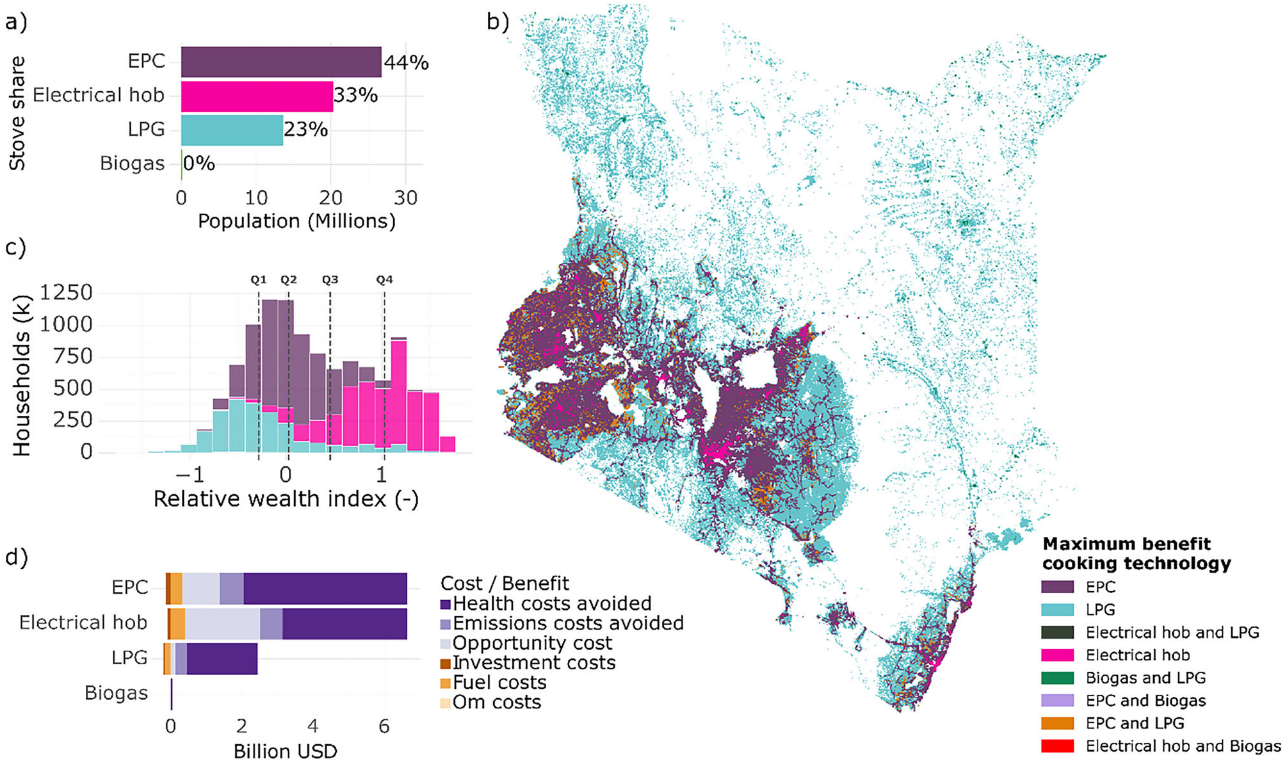

Fig. 3 | Summary without integrated planning (prioritized based on highest population density). **a** The stove shares with highest net-benefit, **b** geospatial distribution of stoves with highest net-benefit, **c** number of households selecting each category of stove in relation to RW. The dashed lines show the borders between quintiles and **d** costs and benefits for each stove selected.

Simultaneously, the investment cost in the cooking sector ranges between 0.4 and 0.5 billion regardless of whether an integrated approach is used or not. It is worth noting that, depending on the number of households adopting electric cooking, there may be a need in investments for adding capacity. In the OnStove-scenarios that are not soft-linked this cost is not included, while the scenarios with soft-linking rely on OnSSET's cost of adding new capacity. This means that the costs for OnStove most likely underestimate the total costs needed for the transition. The cost of adding capacity in OnSSET is incorporated into the LCoE calculations, which is reflected by the fuel costs of the electric options in OnStove increasing with a soft-link. While the total net-investments for both OnSSET and OnStove increase from between 3.7 and 3.8 to between 4.5 and 5.3 billion USD, the average LCoE for the end-user decreases with an integrated approach. The largest decrease in LCoE is in the two lowest wealth quintiles. This shows that targeted subsidies for electricity and electric stoves aimed towards the poorest could benefit the progress towards both indicators of SDG 7.1. While the analysis shows clean options to provide the highest net-benefit, the analysis does not do any assessment on these options' affordability. If any of the scenarios here are to be realized there is a need for subsidies or crediting options. With subsidies, it is important that they are targeted to those that would benefit from them the most. This could encourage uptake of subsidized fuels while minimizing the costs to society.

The results in Kenya highlights large benefits of transitioning to clean cooking. The integrated scenarios avoid between 45,000 and 48,000 deaths across the years covered in the analysis. This is lower than what is currently estimated to be the deaths caused by traditional cooking in Kenya (21,500 deaths/year[26]). This can be explained by mainly two factors. Firstly, we assume a linear increase towards clean cooking access, meaning that traditional cook stoves will still be used (to a decreasing extent) until the final year of the analysis. Secondly, there is a cessation lag in the morbidity and mortality calculations causing the health benefits to only be fully realized after the fifth year following stove-switch. GHG emissions avoided range from 44 to 53 million tonnes in our scenarios during the modeling period. In comparison, the Ministry of Energy estimates the emissions of carbon dioxide, methane, nitrous oxide, carbon monoxide, nitrogen oxides, and black and organic carbon caused by current cooking practices to amount to 20.5 million tonnes of CO_2-eq annually[18]. Time saved across our scenarios is around 1.6 h per household and day. The World Bank estimates that the time of fuel collection ranges vastly between geographies (from 30 min to 6 h a day)[27] and the International Energy Agency estimates that the average collection time for cooking fuels in Kenya is around 1 h per household per day[28].

There are limitations in the work presented here that future research should aim at overcoming. Firstly, this analysis has utilized two specific tools, OnSSET and OnStove. This will inherently result in specific biases due to how the tools are set up and their respective objective functions. Had another tool or a different objective function been selected in OnSSET or OnStove the results could have looked different. This is also true regarding the case study. The analysis presented here is specific to the context of Kenya. Future research should employ the method presented here (or a similar one) to other geographies to see if the conclusions presented still hold true. Countries with vastly different starting points in terms of electricity and clean cooking access will behave differently and the differences between integrated and non-integrated scenarios may be more pronounced. Additionally, it is important to acknowledge Kenya-specific uncertainties, such as political priorities changing, rapid changes in electricity and clean cooking demand, price fluctuations for fuels and technologies and regional disparities that are always present in these types of large-scale planning exercises. This could impact the goals set by governments and change the underlying assumptions that have been employed by the authors here. Secondly, OnStove is programmed to run with a spatial resolution of 1 km. This forces the clusters of OnSSET to be generated using raster datasets of the same resolution. Using the resolution of 1 km for cluster generation increases the size of the clusters, which has been shown to impact the perceived competitiveness of different technology configurations in previous research [25]. In the scenarios presented here some

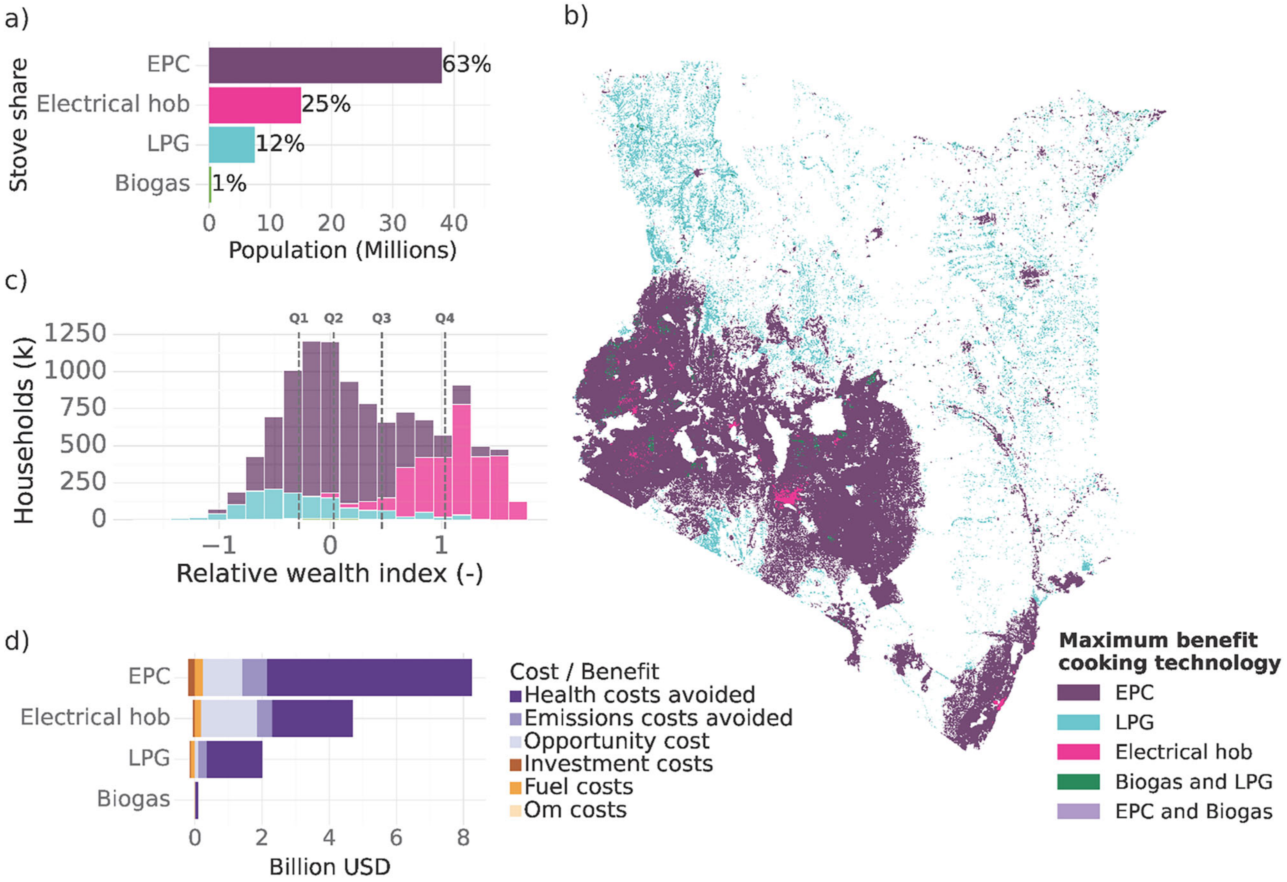

Fig. 4 | Summary integrated scenario (prioritized based on highest population density). **a** Stove shares with highest net-benefit, **b** geospatial distribution of stoves with highest net-benefit, **c** number of households selecting each stove in relation to RW. The dashed lines show the borders between quintiles and **d** total costs and benefits for each stove selected.

settlements increase in size to such an extent that the population density becomes too low to justify grid or mini-grid connections. This in turn risks reducing the share of electric cooking as it is assumed that stand-alone systems cannot sustain the additional load that comes with electric cooking (consequently removing it as an option). Future research should aim at running OnStove at a higher resolution or employing a different clustering algorithm in OnSSET, minimizing the discrepancies between the tools. Thirdly, while the integrated scenarios change electricity demand in every iteration, there is no modeling of how the power plant mix and generation cost of the grid changes with differing electricity demands. Future research should aim at linking the workflow described here to a capacity expansion model. This is especially important as fuel and investment costs in the electricity sector are significant parameters in the cost-benefit equation. Moreover, Kenya has a considerable share of its population currently connected to stand-alone systems. People connected to stand-alone systems tend to use less electricity than those connected to more large-scale solutions and are therefore often missed in the nighttime light maps used in geospatial tools to identify electrified populations. This portion of the population may not see a need to change to a more centralized option in the near future and this would impact the least-cost technology mix and the LCoE. Furthermore, this means that the investment costs given by OnSSET may be overestimating the investments needed in these types of systems. This may be the case especially in areas with large numbers of nomadic pastoralists, that move often. This does however not impact OnStove or the net-benefit equation used to select which stove maximizes net-benefits, as stand-alone systems are assumed to not be able to supply the electricity needed to use an electric stove. Furthermore, it is important to note that several aspects important for estimating the likelihood of transition have not been modeled. These parameters range from mobility issues and infrastructure access to less technical issues such as household internalities and affordability. Future research should aim at capturing these better both in geospatial applications and also in clean cooking modeling. Also, regarding the electrification analysis, a first limitation is that OnSSET minimizes LCOE as a proxy for least-cost electrification, which does not capture delivered prices or system-wide costs such as transmission, distribution, balancing, and policy charges. A second limitation is that the model is implemented in discrete time steps rather than through a fully dynamic optimization, and therefore does not endogenize technology stock turnover or construction lead times. Future work could complement this settlement-level screening with system models such as PyPSA[29] or OSeMOSYS[30], which jointly optimize generation, networks, and operations over time. Lastly, future research should aim at modeling fuel stacking in OnStove, which is currently not possible. Stacking of stoves, especially when a clean option is stacked with a traditional one, will affect the costs of both OnSSET and OnStove as well as the benefits seen following stove-switch. By assuming full adoption and disallowing mid-life switching, our analysis likely overestimates adoption of clean stoves, overstates cost savings, and exaggerates health gains since, in reality, many households continue to use polluting fuels alongside modern ones.

Methods

We base our integrated approach on the soft-linking of OnSSET[20,31,32] and OnStove[33]. Both tools draw from geospatial data to calculate costs (and in the case of cooking, benefits) of reaching different access goals. OnSSET was selected as it is, at the time of writing, the most widely used open-source geospatial electrification tool, while OnStove was selected as it is currently the only available geospatial clean cooking tool. See the Supplementary File for a list of geospatial datasets used in each tool. Each tool is run first

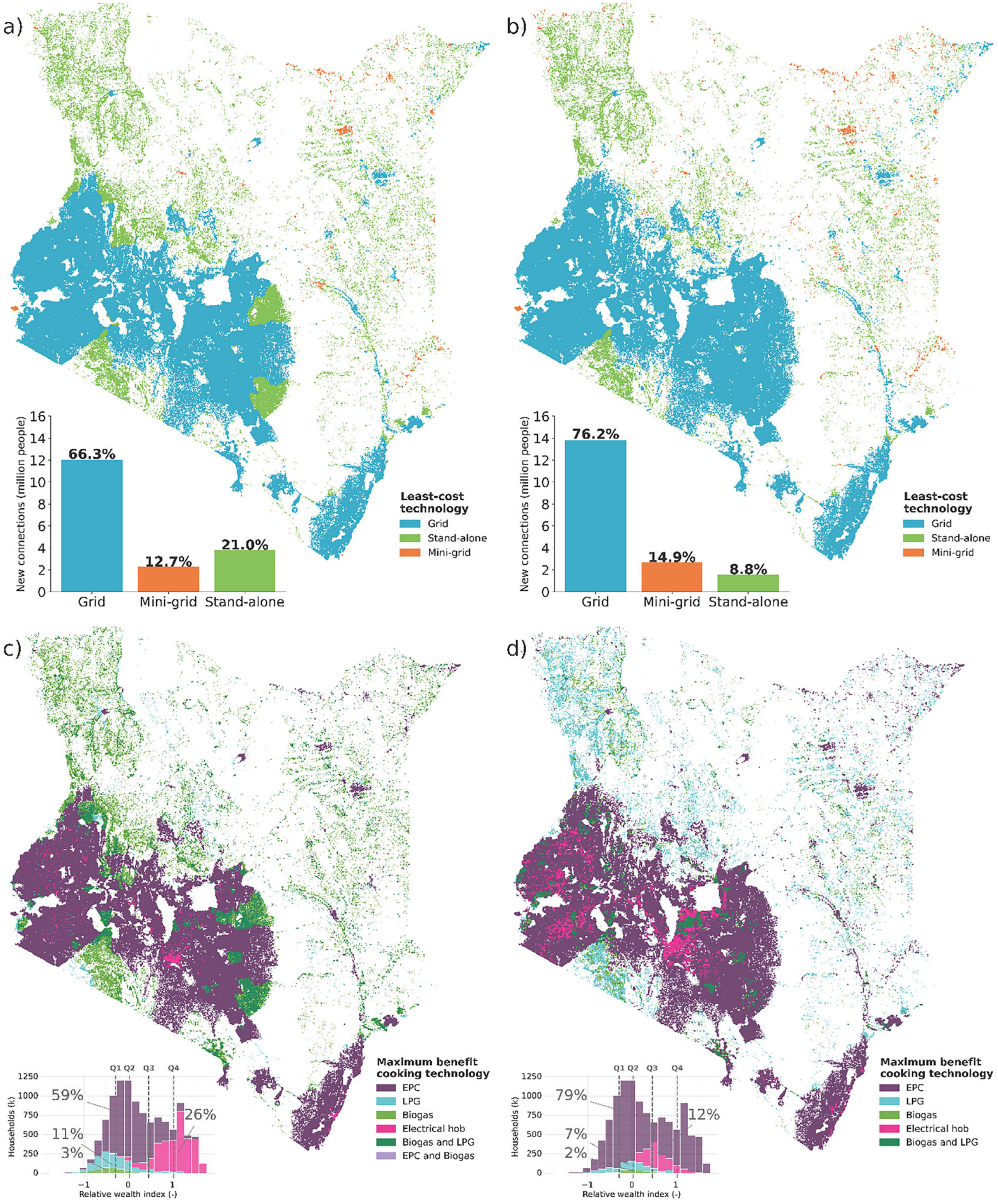

Fig. 5 | Main results for OnSSET and OnStove when prioritizing based on costs and benefits. **a** Spatial distribution of different technology categories in OnSSET and the share of new connections for each when prioritizing based on highest current costs, **b** spatial distribution of different technology categories in OnSSET and the share of new connections for each when prioritizing based on highest current drawbacks, **c** OnStove results when prioritizing based on highest current costs showing the spatial distribution of stoves as well as population shares of each stove in relation to the five wealth quintiles and **d** OnStove results when prioritizing based on highest current drawbacks showing the spatial distribution of stoves as well as population shares of each stove in relation to the five wealth quintiles.

separately and then soft-linked. This gives the ability to compare how electrification and clean cooking scenarios are impacted by an integrated approach. Both tools, the integrated approach and scenarios, are described below.

Least-cost electrification

OnSSET's workflow consists of two parts: first, a calibration of the Area of Interest (AoI) and second, a least-cost electrification analysis. In the calibration, the current electricity access rates and urban population are

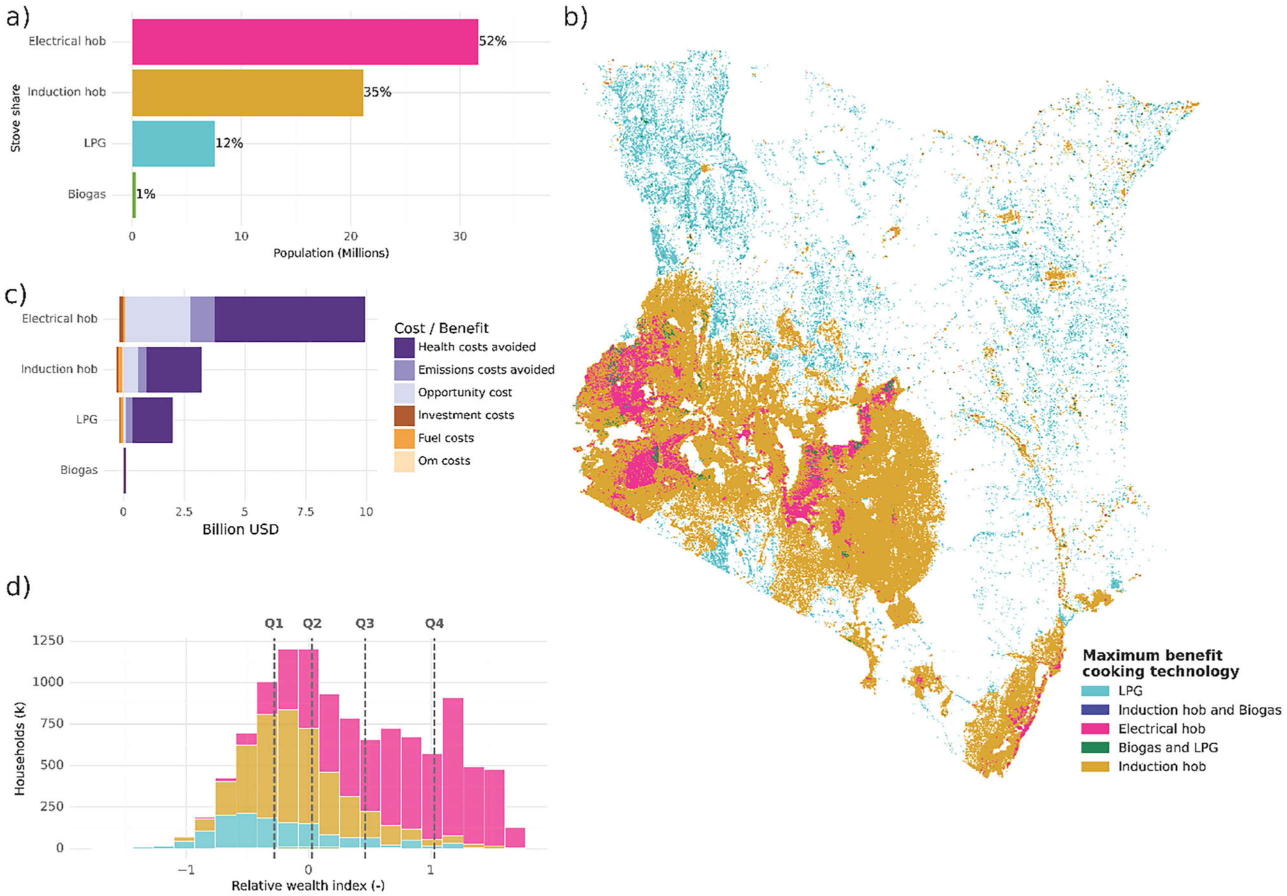

Fig. 6 | Summary of the results in the case with soft-linking, but without EPCs. **a** The stove shares with the highest net-benefit, **b** the spatial distribution of stoves with the highest net-benefit, **c** each category of costs and benefits included in the analysis for each stove and **d** the number of households selecting each category of stove in relation to their RW. The dashed lines show the borders between quintiles.

modeled to match input data provided by the user. The urban calibration ensures that the estimates of urban population are accurate by classifying all settlements with the highest population density as urban until the correct urban rate has been reached. This is done simultaneously to a population calibration ensuring the correct number of people inhabit the AoI. For the calibration of currently electrified population, OnSSET accounts for three geospatial datasets: population density, nighttime light intensity and distance to current electricity-related infrastructure (this can be either distribution transformers, medium- or high-voltage lines)[21]. The electrification calibration gives the three datasets thresholds (minimum population, minimum nighttime light intensity and maximum distance to infrastructure). All settlements falling within the thresholds are electrified. OnSSET compares the electrified population as calibrated to the actual electrification rate given by the user iteratively. If the calibration fails to meet the actual electrification rate, OnSSET alters the thresholds to either relax or tighten the requirements.

After calibration, OnSSET calculates the LCoE for all technology configurations included. LCoE is defined as the lowest possible price point for electricity that allows the system to break even during its lifetime. Whichever technology configuration minimizes LCoE in each settlement is chosen[20]. LCoE for the stand-alone technologies includes all generation system costs (including storage), the mini-grid technologies include the generation system costs and the necessary distribution network, while the grid costs include the cost of extending and strengthening the grid[34]. We include stand-alone PV (photovoltaics), mini-grid hydro, and mini-grid PV-diesel hybrids as possible off-grid solutions in this study. The output of OnSSET includes relevant information for each settlement (e.g., minimum LCoE and the technology configuration minimizing LCoE).

Cost-benefit analysis for cooking

OnStove compares the net-benefits of different stove options across an AoI, selecting whichever stove can provide the highest net-benefit in each sq. km[33]. The net-benefit is defined as combined costs (capital, fuel, and operation and maintenance) minus combined benefits (reduced morbidity, mortality, emissions, and time used to collect fuels and cooking)[33].

OnStove's workflow has two main parts: calibration and net-benefit calculations. The calibration step of OnStove is similar to the one in OnSSET. The total, urban, and electrified populations are calibrated using different datasets and inputs provided by the user. The population calibration is identical to OnSSET. For urban calibration, OnStove gives the user the ability to do it as in OnSSET or to use a geospatial representation of urban classification directly from an external dataset. After the urban calibration, OnStove calibrates the electrification rate to match the rate given by the user using the same datasets as in OnSSET. The electrification calibration is a multi-criteria analysis giving weights to population density, nighttime light intensity and distance to closest electricity-related infrastructure (this can be either distribution transformers, medium- or high-voltage lines). The combined weights determine the electrification rates in different cells across the AoI.

After calibration, the different parameters in the net-benefit equation are calculated (for a detailed description of the calculations included in OnStove's net-benefit equation, refer to Khavari et al.[33]). The net-benefit is calculated for all stoves in all cells of the AoI as long as the fuel is available (electric and biogas stoves are not available in cells without electricity access or biogas availability, respectively). As all benefits and costs in OnStove are in comparison to the current situation (baseline), OnStove first determines the current stove shares across the different cells. In this study, we use data collected by Nuvoni for shares of different cook stoves in urban and rural

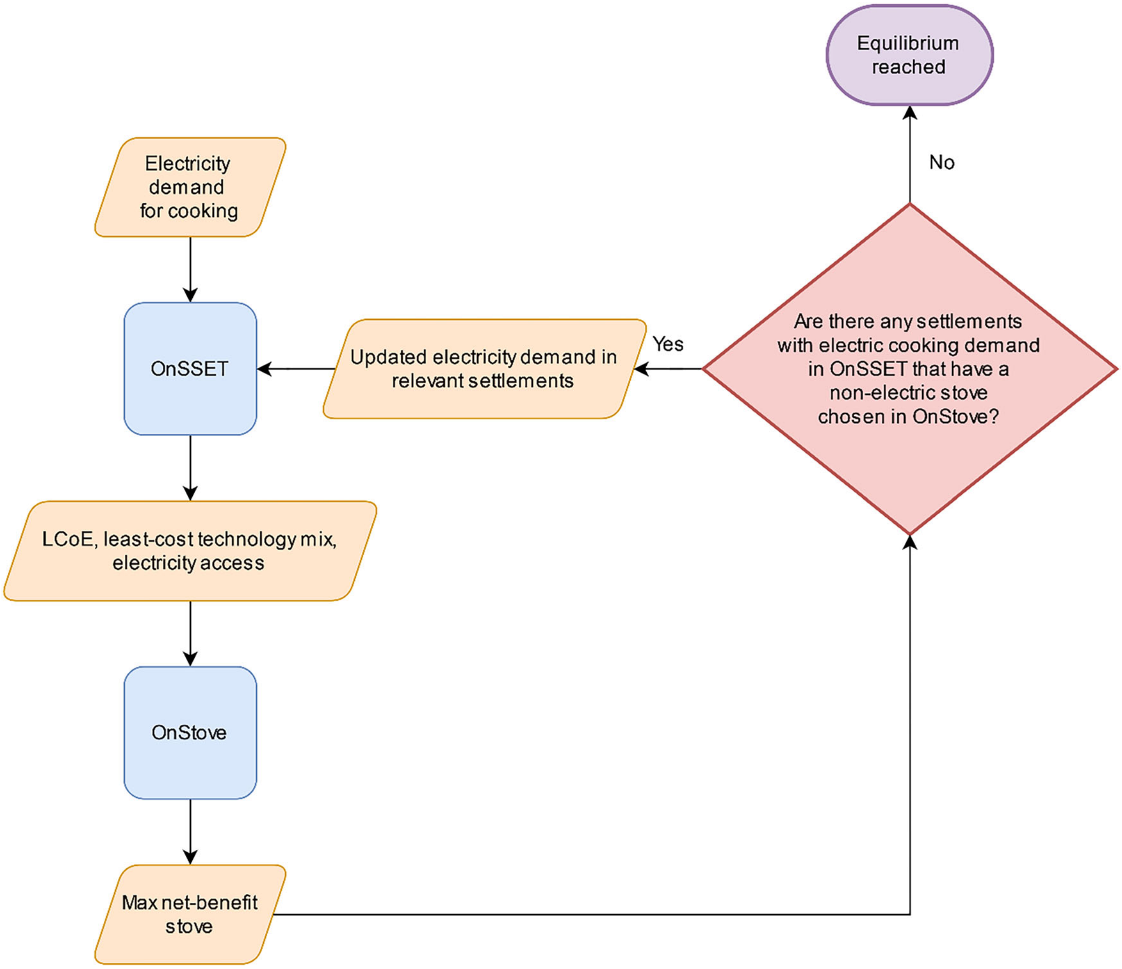

Fig. 7 | Overview of the soft-link workflows.

settlements (see the Supplementary File). This data describes primary stove shares across Kenya representative at national, urban, and rural levels. The stoves included in the analysis are: charcoal ICS, biomass ICS, traditional biomass, traditional charcoal, LPG, biogas, ethanol, electric pressure cooker (EPC), electric hob-stoves and electric induction-stoves.

Integrated energy planning

We soft-link the two tools by first running OnSSET and then using selected outputs for a subsequent OnStove analysis. After running OnStove, the OnSSET runs are repeated taking into account which settlements maximize net-benefits using an electric option as indicated by OnStove. The process is detailed in the sections below.

OnSSET can be run by either explicitly selecting a demand for urban and rural settlements or by using a geospatially diversified demand based on other geospatial datasets. Here, we use the latter option. The datasets used to estimate the demand are nominal GDP and poverty rates (population living below 1.90 USD per day). We classify each one of these datasets into five classes ranging from one to five (one for low GDP or high poverty, and five for the opposite cases). We translate the combined scores, which also range between one and five, to the five electricity access tiers of the Multi-Tier Framework (MTF). Following this, we use Eq. 1 to estimate the amount of electricity per year needed to cook per household.

$$f = \frac{E * \frac{meals}{day} * 365}{eff} \tag{1}$$

Where, E is the final energy needed to cook a meal (1.64 MJ for a household of four[23]) and *eff* is the efficiency of the stove. The electric stove with the lowest efficiency (and hence the highest electricity need) in our study has an efficiency of ~74%. This leads to an electricity requirement of approximately 674 kWh/household/year. We add this demand on top of all settlements falling below MTF tier 4 in the GDP-poverty classification (tier 4 or higher is assumed to not need additional electricity to cook). The outputs from OnSSET used in OnStove are the current electricity access rates (which overwrites the one generated by OnStove itself), the least-cost technology choice in different settlements and the LCoE. We use the least-cost technology mix to estimate who can cook with electricity, assuming cooking can only be done with a mini-grid or grid connection. The LCoE (in USD/kWh) becomes the new fuel cost for electric stoves in the net-benefit equation.

After running OnSSET, OnStove is run. Whatever settlement that is found to be a potential candidate for electric cooking, but where electric cooking does not maximize net-benefits, gets their cooking requirements in OnSSET removed after which OnSSET is re-run. This creates an iterative process, which we repeat until equilibrium is reached. Equilibrium here refers to a case where the load in OnSSET no longer needs altering. See Fig. 7 for an overview of the workflow.

The soft-link overcomes two issues highlighted in Khavari et al.[33]. Firstly, it enables fuel cost for electricity to be spatially disaggregated based on OnSSET-results. This in turn gives a more accurate representation of electricity costs across electrified settlements as OnStove does not model the transmission and distribution costs itself. Secondly, it enables a deeper understanding of how increased electricity access could drive a clean cooking transition. The second point is especially important as Khavari et al. highlight how electricity has, more often than not, the highest net-benefit when available[33]. OnStove does not account for increased electricity access rates, which we overcome with the soft-link.

To run the analysis, modifications are done to both tools. Both tools build on spatial representations of population. OnSSET uses aggregated population clusters and OnStove uses raster populations. To use the results of one tool in the other, the population need to be geospatially aligned. This is ensured by producing the OnSSET-cluster using the same 1 km resolution raster that is used in OnStove. This minimizes the mismatch between the two tools. Furthermore, the previous version of OnStove does not provide a timeline. Instead, the tool calculates the net benefit assuming that the switch happens overnight. The missing temporal dimension in OnStove creates a mismatch between the results when compared to OnSSET, as the latter can model across several years. Therefore, here we add a timeline to OnStove, assuming a linear increase in clean cooking access rates each year. The order of settlements receiving clean cooking can be prioritized three ways (prioritization methods). The user can choose to prioritize based on highest current cost per household, the highest current drawbacks per household or population density. Every year is modeled separately, and as an invested stove reaches the end of its lifetime (and only then), the net-benefit is calculated for all stoves again, giving the possibility to change stoves. Hence, a different prioritization may influence the final stove mix simply due to electricity access reaching a specific settlement after clean cooking access.

Scenarios

We explore different scenarios aimed at increasing understanding around the developments done in OnStove and potential clean cooking pathways for Kenya. In all scenarios, the start year is 2021 (first results are therefore produced for 2022) and we assume that Kenya reaches universal electricity and clean cooking access by 2026 and 2028, respectively, as aimed for in their national policies. The scenarios are all run first without a soft-link and then with a soft-link to assess the differences in results. For each one of the prioritization methods included in OnStove one scenario is developed. As previous research has indicated that Electric Pressure Cookers (EPCs), while being highly efficient and clean, are sometimes incompatible with local dishes and cooking practices[23], a scenario without EPCs using the population density prioritization is also developed to mimic a case in which other alternatives are favored over EPCs. The four scenarios are:

- Clean cooking reaches first those areas with the highest population density.
- Clean cooking reaches first those areas with the highest current costs.
- Clean cooking reaches first those areas with the highest current drawbacks.
- Clean cooking reaches first those areas with the highest population density, but without EPCs.

Data availability

All the data to support the findings is presented and summarized in the supplementary information.

Received: 28 April 2025; Accepted: 13 November 2025;

References

1. Nerini, F. F. et al. Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nat. Energy* **3**, 10–15 (2018).
2. Jeuland, M. et al. Is energy the golden thread? A systematic review of the impacts of modern and traditional energy use in low- and middle-income countries. *Renew. Sustain. Energy Rev.* **135**, 110406 (2021).
3. Rosenthal, J., Quinn, A., Grieshop, A. P., Pillarisetti, A. & Glass, R. I. Clean cooking and the SDGs: integrated analytical approaches to guide energy interventions for health and environment goals. *Energy Sustain. Dev.* **42**, 152–159 (2018).
4. Nathwani, J. & Kammen, D. M. Affordable energy for humanity: a global movement to support universal clean energy access. *Proc. IEEE* **107**, 1780–1789 (2019).
5. IEA, World Energy Outlook 2025, International Energy Agency. Accessible at: https://www.iea.org/reports/world-energy-outlook-2025.
6. Das, I. et al. The benefits of action to reduce household air pollution (BAR-HAP) model: A new decision support tool. *PLoS ONE* **16**, e0245729 (2021).
7. Batchelor, S. et al. Mutual support—modern energy planning inclusive of cooking—a review of research into action in Africa and Asia since 2018. *Energies* **15**, 5805 (2022).
8. Brown, E., Leary, J., Davies, G., Batchelor, S. & Scott, N. eCook: what behavioural challenges await this potentially transformative concept? *Sustain. Energy Technol. Assess.* **22**, 106–115 (2017).
9. Leary, J., Leach, M., Batchelor, S., Scott, N. & Brown, E. Battery-supported eCooking: a transformative opportunity for 2.6 billion people who still cook with biomass. *Energy Policy* **159**, 112619 (2021).
10. Batchelor, S., Brown, E., Scott, N. & Leary, J. Two birds, one stone—reframing cooking energy policies in Africa and Asia. *Energies* **12**, 1591 (2019).
11. Sustainable Energy for All. *Data Standards for Integrated Energy Planning*. (2020).
12. United Nations. *Theme Report on Energy Access - Towards the Achievement of SDG 7 and Net-Zero Emissions*. (2021).
13. Lombardi, F., Riva, F., Sacchi, M. & Colombo, E. Enabling combined access to electricity and clean cooking with PV-microgrids: new evidences from a high-resolution model of cooking loads. *Energy Sustain. Dev.* **49**, 78–88 (2019).
14. Sánchez-Jacob, E. et al. Joint optimal planning of electricity and modern energy cooking services access in nyagatare. *Energies* **14**, 4093 (2021).
15. Lee, S. J. et al. Investigating the necessity of demand characterization and stimulation for geospatial electrification planning in developing countries. (2019).
16. Koech, W. et al. *Environmental and Social Screening Project Report for Last Mile Connectivity Project*. (2016).
17. KOSAP Project Components -. https://www.kosap-fm.or.ke/kosap-project-components/.
18. MoE. Kenya Household Cooking Sector Study: Assessment of the Supply and Demand of Cooking Solutions at the Household Level. (2019).
19. DRAFT ENERGY (INTEGRATED NATIONAL ENERGY PLANS) REGULATIONS_2021.pdf. *Energy and Petroleum Regulatory Authority* https://www.epra.go.ke/draft-energy-integrated-national-energy-plans-regulations_2021-pdf/ (2023).
20. Sahlberg, A., Khavari, B., Korkovelos, A., Fuso Nerini, F. & Howells, M. A scenario discovery approach to least-cost electrification modelling in Burkina Faso. *Energy Strategy Rev.* **38**, 100714 (2021).
21. Khavari, B., Sahlberg, A., Usher, W., Korkovelos, A. & Fuso Nerini, F. The effects of population aggregation in geospatial electrification planning. *Energy Strategy Rev.* **38**, 100752 (2021).
22. Sahlberg, A., Khavari, B., Mohamed, I. & Fuso Nerini, F. Comparison of least-cost pathways towards universal electricity access in somalia over different timelines. *Energies* **16**, 6489 (2023).
23. Modern Energy Cooking Services (MECS). *An In-Depth Exploration of Cooking Entirely with Electricity in Kenya*. (2023).
24. https://www.the-star.co.ke/authors/amadala. Kenya's blackouts way above global average - EPRA. *The Star* https://www.the-star.co.ke/business/kenya/2022-02-24-kenyas-blackouts-way-above-global-average-epra/.
25. Yumkella, K., Batchelor, S., Haselip, J. A. & Brown, E. *Solving the Clean Cooking Conundrum in Africa: Technology Options in Support of SDG7 and the Paris Agreement on Climate Change* (DTU, 2021).
26. Shilenje, Z. W., Maloba, S. & Ongoma, V. A review on household air pollution and biomass use over Kenya. *Front. Environ. Sci*. **10**, https://doi.org/10.3389/fenvs.2022.996038 (2022).

27. Opening Opportunities, Closing Gaps | ESMAP. https://esmap.org/ESMAP_Opening_Opportunities_Closing_Gaps.
28. International Energy Agency (IEA). A Vision for Clean Cooking Access for All. (2023).
29. Brown, T., Hörsch, J. & Schlachtberger, D. PyPSA: Python for Power System Analysis | Journal of Open Research Software. https://doi.org/10.5334/jors.188 (2018).
30. Howells, M. et al. OSeMOSYS: the open source energy modeling system: an introduction to its ethos, structure and development. *Energy Policy* **39**, 5850–5870 (2011).
31. Mentis, D. et al. Lighting the world: the first application of an open source, spatial electrification tool (OnSSET) on Sub-Saharan Africa. *Environ. Res. Lett.* **12**, 085003 (2017).
32. Korkovelos, A., Khavari, B., Sahlberg, A., Howells, M. & Arderne, C. The role of open access data in geospatial electrification planning and the achievement of SDG7. An OnSSET-based case study for Malawi. *Energies* **12**, 1395 (2019).
33. Khavari, B., Ramirez, C., Jeuland, M. & Fuso Nerini, F. A geospatial approach to understanding clean cooking challenges in sub-Saharan Africa. *Nat. Sustain*. 1–11 https://doi.org/10.1038/s41893-022-01039-8 (2023).
34. Sahlberg, A. et al. Exploring long-term electrification pathway dynamics: a case study of Ethiopia. *Discov. Energy* **3**, 1 (2023).

Acknowledgements

The work done at KTH with regard to this research was supported by the Clean Cooking Alliance (CCA) through funding from the Norwegian Agency for Development Cooperation and the Netherlands Ministry of Foreign Affairs. F. Fuso Nerini and C. Ramirez Gomez also aknowledge funding from the Climate Compatible Growth Programme (CCG). CCG is funded by the UK governments Foreign Development and Commonwealth Office (FCDO). We thank S. Lloyd (CCA), D. Mentis (WRI), J. Stockman (WRI) and A. Onsare for valuable inputs and discussions. Neither these individuals nor the funding agencies should be held responsible for any erroneous facts or interpretations presented in this paper. These are solely the responsibility of the authors.

Author contributions

B.K. did the literature review, data curation, software developments, formal analysis, wrote the original manuscript draft and led the conceptualization. A.S. contributed to the software developments and conceptualization. C.R. contributed to the software developments. S.O. drafted the Kenya case study. E. O. drafted the Kenya case study and collected data on the ground. K.N., D.R., and V.O. collected data on the ground. A.G. supported data gathering, stakeholder consultation and supervision. F.F.N. provided supervision throughout the analysis and manuscript writing and revisions. All authors were involved in reviewing the manuscript.

Funding

Open access funding provided by Royal Institute of Technology.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44406-025-00017-1.

Correspondence and requests for materials should be addressed to Francesco Fuso Nerini.