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Advancing Energy Access Modelling with Geographic Information System Data

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Abstract

One of the main goals in pursuing sustainable development is to provide universal access to modern energy services, notably through the use of off-grid renewable energy technologies. To date, integrated assessment models (IAMs) poorly address energy access targets. In the context of research dedicated to energy scenarios and climate change mitigation in Africa, we attempt to advance the representation of energy access in one such IAM by using GIS data. In a case study for Ethiopia with the TIAM-ECN model, we demonstrate that by enriching an IAM with information derived from GIS databases, insights are obtained that better capture the dynamics of energy access developments, in comparison to conventional IAM analysis of energy technology deployment pathways. When duly accounting for the geographical spread in demography and technology costs in a developing country, we find that many people may gain access to electricity in remote areas thanks to the availability of affordable off-grid power production options that render expensive grid extensions unnecessary. This effect is not explicitly accounted for in most traditional IAMs. By the middle of the century, off-grid technologies could provide affordable electricity to 70% of the Ethiopian population, based almost entirely on renewable sources such as wind, solar and hydropower.

Keywords Integrated assessment model (IAM) · Off-grid electricity generation · Renewables · Africa · GIS

Highlights

- We propose a method for using GIS data to enrich energy-economy-environment models.
- Our method allows for better simulating developments in advancing energy access, e.g. in Africa.
- We project universal electricity access in Ethiopia by 2040 thanks to off-grid technologies.
- By the middle of the century, off-grid options could provide electricity to 70% of the population.
- In 2050, more than 95% of off-grid electricity is produced through renewable energy technologies.

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1 Introduction

While in the five North African countries, more than 99% of the population today has access to electricity, in Sub-Saharan Africa, this level is only about 37% (up from 23% in 2000). In Sub-Saharan Africa, approximately 600 million people still live without access to electricity, which is more than in any other part of the world [7, 8]. This number is increasing, because endeavours to get more people connected to electricity supply—though quite successful—are unable to meet rapid population growth: since 2000, the number of people with access increased by approximately 135 million, while the population living without electricity augmented by around 100 million. Such a high number of people remaining excluded from electricity use is at loggerheads with initiatives such as the "Sustainable Energy for All" (SE4All) programme of the UN [24] as well as its "Sustainable Development Goals" (SDGs; see [25]).

Even while advancing access to modern energy services is recognised as one of the main aims of the SDGs, quantitative tools used by energy analysts to inspect how and with what kind of interventions or policies this goal can be furthered poorly reflect issues of energy access and the challenges involved therein. Among these instruments are Integrated Assessment Models (IAMs), which allow for studying interactions between the economy, energy use, and our environment. IAMs enable investigating energy transition pathways in the context of global climate change mitigation and the fulfilment of the targets of the Paris Agreement [2]. Most IAMs, however, do not adequately represent mechanisms that may increase energy access in emerging economies. This is a shortcoming especially in developing countries, where large portions of the population are located in remote areas, such as in most of Sub-Saharan Africa [11]. One of the main bottlenecks is the intrinsic difficulty in bridging the high-level system-oriented approach of IAMs with the strong dependency of energy access development on specific local geographical characteristics such as resources availability, population density and distance from power infrastructure. It is our intention in this paper to make a first step towards addressing this shortcoming. We do so in the context of assessing the future for renewable energy technologies in developing nations and thereby connect to other literature in this domain [12].

Notable recent prior research in this area includes the work of Dagnachew et al. [3] and Lucas et al. [16], who couple an extended version of a rural electrification model by van Ruijven et al. [32] with projections of household electricity consumption from the IMAGE model for Sub-Saharan Africa. Other relevant work focuses on spatially resolved least-cost analysis of on- and off-grid options in Sub-Saharan Africa [23], in Nigeria [19] and in Ethiopia [18]. In these publications, least-cost optimization determines the final technology mix and the level of deployment of centralised versus off-grid options. Cost minimisation, however, is performed outside the IAM, as a result of which interactions between household electricity use and the rest of the energy system may not be adequately reflected. The novel approach presented in this paper aims at taking full advantage of insights from both GIS and IAMs. We achieve this by (i) using GIS analysis to determine the demand for residential electricity as well as the maximum potential of several (renewable and fossil-based) electricity generation technologies, (ii) feeding these into an IAM, and (iii) subsequently optimising the energy system as a whole. Our method to enrich an IAM with information obtained from GIS databases fits in efforts undertaken by the IAM community to advance the use of various types of Big Data for energy systems analysis.

For this purpose, we employ a well-established member of the IAM family, TIAM-ECN. We choose TIAM-ECN for the present study because, among all IAMs, it possesses the most refined geographical disaggregation of the African continent: 17 distinct regions in our most recent version (see [13, 30]). We apply TIAM-ECN to study energy access in Ethiopia, because universal access to electricity is one of the major short-term development targets set by the international community [24, 25]. This paper connects to a case study we recently performed on how the energy system of Ethiopia could transition to a rapid decarbonisation process that allows for meeting its Nationally Determined Contribution (NDC) and the potential role for hydropower therein [29]. Ethiopia's NDC ambitions are particularly significant, as it intends to reduce its projected business-as-usual emissions of 400 $MtCO_2e$ in 2030 by 64% [10]. Of the envisaged GHG emissions reduction of 255 $MtCO_2e$, 130 $MtCO_2e$ should be realised in forestry and 90 $MtCO_2e$ in agriculture, with the remaining 35 $MtCO_2e$ materialised through a combination of GHG abatement efforts in transportation, industry and buildings. The power sector is intended to remain at its current emission level of 5 $MtCO_2e$, although this sector is expected to grow substantially in order to satisfy increasing demand for, and expand access to, electricity. This target sharply contrasts with an expected population growth from around 99 million people in 2015 to approximately 191 million inhabitants in 2050 [26].

In the following, we describe how, for the case of Ethiopia, we have adapted TIAM-ECN to better represent energy access challenges. In section 2 of this article, we describe our GIS analysis and explain how it can be used to improve an IAM like TIAM-ECN. In section 3, we specify how we have enriched TIAM-ECN to enable it to better deal with off-grid electricity generation. Section 4 is dedicated to the description of our scenarios and reports our main modelling results. In section 5, we discuss our findings and list our major conclusions and recommendations for the IAM community and policy makers the like.

2 GIS Analysis

Building on the approach proposed in Strikkers [22], we design a GIS-driven methodology that enables deriving a projection for the number of people that have access to either centralised or off-grid electricity, or both, between 2010 and 2050. At every modelling step in time, we estimate the average willingness-to-pay (WTP) for getting access to electricity. We use the WTP to calculate the maximum feasible expansion of the grid and to determine whether an affordable off-grid technology exists in each of the 1-km^2 raster cells in our GIS layers. The results of our analysis with this methodology are reported in Figs. 1 and 2, in the form of GIS maps that display the geographical distribution of connectivity and the total number of people attaining access to electricity, respectively.

2.1 Data Sources

Our analysis relies on essentially four main distinct datasets:

1. GIS maps that contain spatially resolved estimates for the levelised cost of electricity (LCOE) for several off-grid electricity generation technologies in Africa: diesel generators, hydropower and solar PV [23];
2. A GIS map with population density data for Africa in 2010 [34];
3. A GIS map of electricity grid lines in Africa in 2010 [23];
4. GIS maps for Ethiopia's state borders [20], main cities [5] and water bodies [6].

The first two items are *raster layers*, in which data are stored in a matrix of 1-km^2 raster cells. The last two items

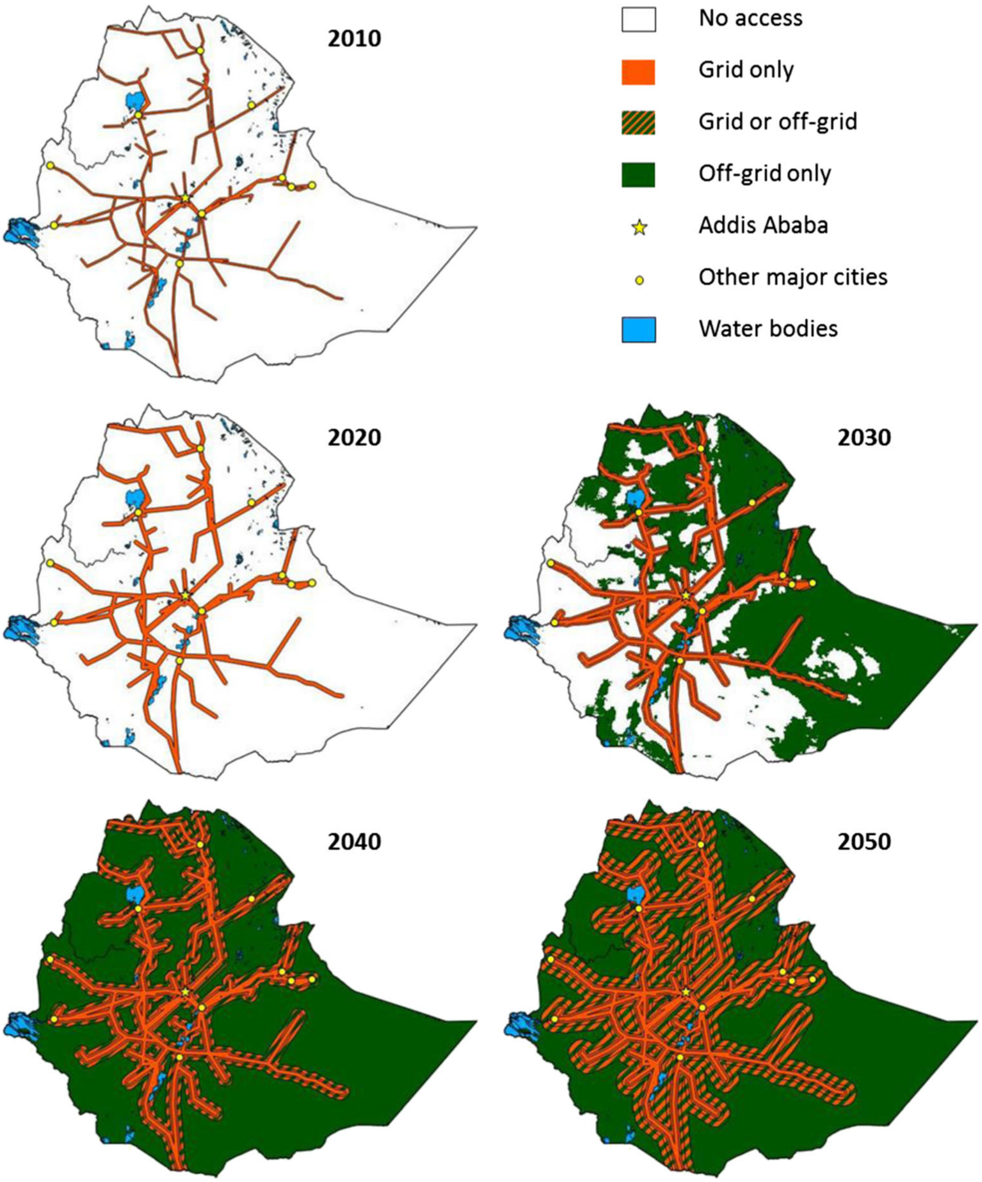


Fig. 1 Electricity access from 2010 to 2050 in Ethiopia: centralised access to the grid is depicted in orange, off-grid connection in green, while zones in which grid expansion can compete with off-grid options are represented as orange-green hashed areas

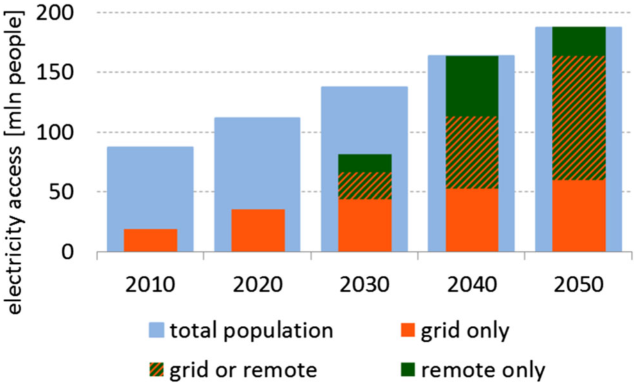


Fig. 2 Electricity access in Ethiopia in terms of the number of people connected to the grid (orange) or to off-grid power production (green), or those that have the choice between these two alternatives (orange-green hashed)

are *vector layers* that store data as geometric shapes such as points, lines and polygons. We use the country boundary map under item 4 to extract the features from items 1 to 3 that fall within the territory of Ethiopia. We create additional LCOE layers for diesel generators, hydropower and off-grid solar PV for the decadal points between 2020 and 2050 by projecting the LCOE maps for 2010 into the future, according to exogenous cost decline rates also applied elsewhere in the TIAM-ECN model for analogous technologies (see, e.g. [31]). The population map (item 3) reports the absolute number of people per square kilometre in 2010. By applying population growth projections from the UNDP [27] to each cell in this layer, we obtain population maps for the decadal points between 2020 and 2050. Other data sources that complement these GIS maps are GDP projections from the UNDP and population and energy access statistics from the World Bank [27, 33].

2.2 Willingness-To-Pay

The first step in our analysis is to estimate the WTP for gaining access to electricity, expressed in \$/MWh. For 2010 we calculate the WTP as:

$$\mathrm{WTP}_{2010} = \frac{\mathrm{EEC}_{2010} \times \mathrm{GDP}_{2010}}{\mathrm{FEC}_{2010}},$$

in which:

- EEC_{2010} is the electricity expenditure coefficient in 2010, expressing the share of income (measured in GDP per capita); people are on average willing to spend on electricity, which we estimate to be 2% based on 2010 electricity generation costs [1];
- GDP_{2010} is GDP per capita in Purchase Power Parity (PPP) terms in 2010, which amounts to 1052 \$ [33];
- FEC_{2010} is final electricity consumption per connected person in 2010, which is 207 kWh [8, 9, 33].

The outcome is $\mathrm{WTP}_{2010} = 101$ \$/MWh. For subsequent years, we assume that the WTP grows proportionally to the logarithm of GDP per capita, which yields $\mathrm{WTP}_{2050} = 270$ \$/MWh. We justify this approach by observing that a correlation appears to exist between access to electricity and the logarithm of GDP per capita (see Supplementary material and [21]).

2.3 Electricity Access Projection

In order to determine the reach of the centralised electricity network in Ethiopia in 2010, we create consecutive buffers around the existing power lines in the 2010 GIS grid map, until the number of people within the buffers matches the total number of people connected to the grid in 2010. We find that a buffer of 3.7 km is sufficient to contain the quoted share of 22% of the population having access to electricity in 2010.

An extension of the grid induces an increase in the electricity price, which reflects the additional capital and operational costs of the new infrastructure. In line with Szabó et al. [23], we assume an electricity price mark-up $ePMU = 3.93$ \$/MWh for each additional 1-km buffer distance around the 2010 grid. To estimate the grid expansion in 2020, we create consecutive buffers around the 2010 grid connection area until the total price increase matches the increase in WTP between 2010 and 2020, as expressed in:

$$\mathrm{BR}_{2020} = \mathrm{BR}_{2010} + \frac{\mathrm{WTP}_{2020} - \mathrm{WTP}_{2010}}{\mathrm{ePMU}},$$

in which BR_y is the buffer distance in year y. Using this approach, we project the grid extension area up to 2050, which results in the orange zones depicted in Fig. 1.

We estimate access to off-grid electricity by comparing the projected LCOE maps with the WTP in each decade. Every raster cell for which there exists an off-grid technology with LCOE below the WTP is given off-grid access: these are the green areas indicated in Fig. 1.

2.4 Results

Figure 1 presents the results of our GIS analysis in five maps, corresponding to the five decades that we inspect until the middle of the century. Different colours are used to distinguish between zones with no access to electricity (white), grid access (orange), off-grid access (green), and areas where both grid and off-grid access are economically viable (hashed orange-green). As one can see, we find that in 2010 and 2020, electricity is accessible exclusively through the central power network. As the WTP increases, the area covered by the grid expands between 2010 and 2020, as can be observed from the thickening of the orange lines: in these areas, off-grid solutions are still too expensive, so the grid can expand without competition. This evolution continues in 2030, but an additional phenomenon kicks in: the combined effects of technology cost reductions and WTP increases make remote electricity affordable in certain areas. This is indicated in Fig. 1 (2030) by the appearance of green patches, which are areas where there is at least one stand-alone or mini-grid technology that falls under the WTP threshold. In 2040, universal access is reached thanks mostly to the increased affordability of off-grid electricity generation. It also becomes visible in 2040 that the grid can be further expanded, but that such expansion takes place in areas in which it needs to compete with the deployment of off-grid technologies, as indicated by the hashed orange-green zones. In the last two decades of our projection, the grid can only achieve additional expansion in competition with off-grid power production.

For the purpose of this paper, we assume that the areas into which the centralised grid has expanded without competition from off-grid options between 2010 and 2030 are no longer available for off-grid access in future years. This assumption simulates a lock-in effect, whereby the presence of the grid discourages investments in off-grid options, which is reflected by the areas that remain orange until 2050. Yet, as can be seen in Fig. 1, the enlargement of the surface in which grid connection becomes affordable continues to expand until 2050, well into zones in which off-grid options had become affordable in earlier decades.

The maps in Fig. 1 can be used, in combination with the population density maps, to estimate the number of people with access to electricity at any point in time during our modelling timeframe. With these maps, it can also be determined whether access to electricity supply is achieved via the grid, off-grid options, or a combination thereof (i.e. a choice between them, in areas where both grid and off-grid options are affordable and their relative costs are among the determinants for the type of connectivity). The result is presented in the bar-chart of Fig. 2, using the same colour scheme introduced in Fig. 1 to differentiate among the various types of access. In light blue, we indicate the total population of Ethiopia, which nearly doubles in a period of about four decades. Figure 2 shows that universal access can be achieved by 2040 and that the affordability of off-grid technologies plays a pivotal role in reaching this objective.

By the middle of the century, nearly 70% of the population could have access to off-grid electricity (green and hashed orange-green portion of the 2050 bar in Fig. 2). For the part of the population that could potentially access both off-grid and on-grid electricity (hashed portion of the bars), the actual 'choice' will ultimately depend not only on cost-competitiveness between grid-connected and off-grid technologies, but also on other factors, such as population density, energy-intensity of local economic activities, availability of local energy sources and feasibility of expanding the grid, just to name a few.

From the data in Fig. 2, we derive residential electricity demand with the equation:

$$\mathrm{DEM}_y = \mathrm{DEM}_{(y-10)} \left(\frac{\mathrm{POP}_y}{\mathrm{PPH}_y} \Big/ \frac{\mathrm{POP}_{(y-10)}}{\mathrm{PPH}_{(y-10)}} \right)^{\mathrm{DF}_y},$$

in which DEM_y is the residential electricity demand in year y, POP is the number of connected people, PPH is the number of people per household, DF is a decoupling factor (to reflect autonomous energy efficiency improvements) and the subscript y indicates the year, ranging from 2020 to 2050 in steps of 10 years. The formula is calibrated to the 2010 electricity demand for residential appliances, $\mathrm{DEM}_{2010} = 4.1$ PJ [8, 9]. The number of connected people at each time step is taken from Fig. 2, while PPH and DF are exogenous assumptions (see, e.g. Loulou and Labriet [15] van der Laan [28], and van der Zwaan et al. [31]). Based on the level of disaggregation in Fig. 2, we separate the residential electricity demand into two components, *grid* and *off-grid*. The former is derived by only considering the grid-connected population (orange segments Fig. 2). The latter is constructed by summing the number of people that have access to either grid or *off-grid* options (hashed segments in Fig. 2) and those that have access exclusively to *off-grid* electricity (green segments in Fig. 2).

The *grid* and *off-grid* residential electricity demands are used as input for the TIAM-ECN model in the remainder of this paper. The disaggregation of residential electricity demand into *grid* and *off-grid* components is one of the key novelties we introduce in this study that provides the link between GIS and IAM analysis. By using GIS to extract a separate projection for the *off-grid* component of residential electricity demand, we improve the way TIAM-ECN simulates competition between deployment of off-grid technologies and additional grid expansion, as well as among off-grid options themselves.

3 TIAM-ECN

TIAM-ECN is a well-established version of the global TIAM model developed under the Energy Technology Systems Analysis Program of the International Energy Agency (IEA-ETSAP). A technology-rich, bottom-up integrated assessment model with global geographical scope, TIAM, is built on the TIMES model generator, as described in detail in Loulou and Labriet [15] and Loulou [14]. TIAM is a linear optimization model that minimises energy system costs in each time-period with perfect foresight. The objective function includes capital, operation and maintenance, as well as fuel and trading costs.

Building on a database of hundreds of energy-related processes and commodities, TIAM-ECN simulates the entire global energy system from resource extraction to end-use over a period that spans the entire twenty-first century. For a general description of the reference energy system of TIAM-ECN, see Syri et al. [36]. TIAM-ECN has been used successfully in several different sectors and domains, such as transportation (see, e.g. Rösler et al. 37), power supply (Keppo and van der Zwaan [38]), burden sharing among countries for global climate change control [13] and global and regional technology diffusion (see, e.g. van der Zwaan et al. [39]). In the current set-up of TIAM-ECN, the world is disaggregated in 36 distinct regions ([28, 30]; Dalla Longa et al. [35]). Ethiopia is modelled as a separate 'region', enabling the country-level analysis described here.

For the present paper, we enriched the input database of TIAM-ECN with a more detailed description of a set of off-grid electricity production technologies, namely, wind, solar PV, hydropower and diesel generators. Although off-grid wind was not assessed in the GIS analysis, we included it in the TIAM-ECN input database. The rationale behind this choice is that in this study, we use the results of the GIS analysis to estimate overall demand for residential electricity, split into two components: *off-grid* and *grid*. All off-grid, respectively grid-connected, processes in TIAM-ECN are eligible (within appropriate constraints) to fulfil these demand components, and we let the model deploy the most cost-efficient options.

3.1 Off-grid Electricity Processes in TIAM-ECN

In Fig. 3, we show projections of levelised costs of electricity (LCOE) for our off-grid power production options. These comprise renewable energy and fossil fuel-based technologies, and include for each process stand-alone as well as mini-grid implementations. We assume that stand-alone solar PV and wind installations are equipped with battery systems to partially compensate for intermittency. Our LCOE estimates are based on investment and operational costs found in databases from the World Bank [33] combined with exogenous cost reduction rates (see, e.g. [31] and references therein). Storage and grid connection cost mark-ups are included for stand-alone and mini-grid systems, respectively.

Wind energy and PV yield at present relatively high power production costs, well above their hydropower and diesel-based counterparts. The former (renewable) options, however, are subject to substantial learning-by-doing as a result of which their costs reduce over the next few decades. For PV, we assume that cost reductions are more significant than for wind power given the higher learning rate observed for PV to date. There is a large cost difference between stand-alone and mini-grid wind energy, since the latter profits from a sizeable economies-of-scale effect. We do not assume such a wedge between stand-alone and mini-grid PV, as the absence of large infrastructural requirements precludes significant economies-of-scale opportunities. For small-scale hydropower and diesel-based electricity generation, we assume negligible learning opportunities and only a small scaling effect between stand-alone and mini-grid alternatives. As can be seen in Fig. 3, we assume that mini-grid wind energy and both solar PV options (stand-alone and mini-grid) can be deployed at lower costs in 2050 than electricity production through hydropower and diesel generators.

3.2 Scenarios

Based on the results of our GIS analysis, we separate electricity demand for use in residential appliances into two components: *grid demand* from the central power network and *off-grid demand* from off-grid technologies or an additional (expensive) extension of the grid. In order to exemplify the effects of splitting residential demand for electricity in TIAM-ECN, we create two scenarios:

CENT	Centralised demand: Demand for electricity used in residential appliances derives exclusively from grid-connected households.
SPLIT	Split demand: Electricity for use in residential appliances is split into *grid* and *off-grid*, according to the results of our GIS analysis.

The CENT and SPLIT scenarios are both business-as-usual projections, in the sense that they assume no climate control policies enacted after 2010. The difference in the two scenarios lies entirely in the way residential electricity demand is represented. In CENT, we only account for demand for residential electricity from grid-connected households, as has been common practice in all TIAM-ECN and most other IAM studies to date. The approach followed in this scenario quite adequately represents the situation in North America and most countries in, e.g. Europe or elsewhere in the OECD, but it is highly inaccurate for nearly all of Sub-Saharan Africa, where large portions of the population are located too far from the existing power network and will not have access to the grid anytime in the near future. In SPLIT, we obviate this inaccuracy by using the results of our GIS analysis to differentiate electricity demand between *grid* and *off-grid*. Households located near the grid (*grid only* zones in Fig. 1) can access exclusively centrally produced electricity. Households far from the grid capable of affording electricity consumption (*off-grid only* zones in Fig. 1) can gain access through off-grid options. In areas where both grid connection and off-grid options are affordable (*grid or off-grid* zones in Fig. 1) grid expansion is occurring in competition with the deployment of off-grid technologies. In the latter case, a cost mark-up is included in TIAM-ECN to account for the

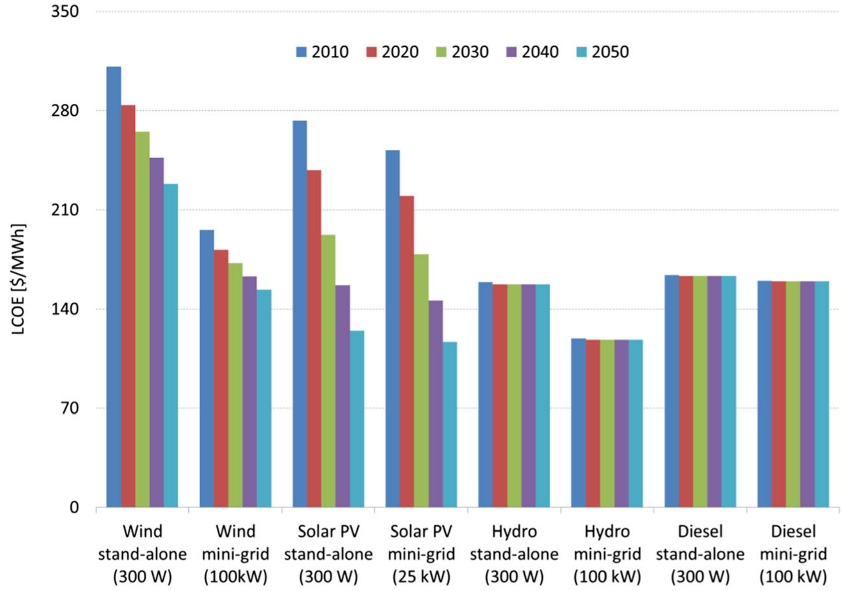


Fig. 3 Levelised costs of electricity for 8 off-grid power production options until 2050

additional costs of expanding the grid well beyond its current extension. As an illustrative value, we took for the mark-up the WTP in 2030, i.e. 188 $/MWh.

3.3 Constraints

An analysis of the LCOE maps reveals that diesel generators and solar PV are always available in all green and hashed raster cells in Fig. 1, whereas off-grid hydroelectricity only exists in certain areas. By intersecting the hydro LCOE layers with the maps in Fig. 1, we calculate the maximum number of people that can have access to *off-grid* hydroelectricity in each period, and set an upper limit for the deployment of this technology. We find that the maximum production of electricity from off-grid hydropower is 0.5, 2.6 and 3.5 TWh respectively in 2030, 2040 and 2050. The increase between 2030 and 2040 is due to a combination of the expansion of the area where people can afford off-grid electricity (that is more zones suitable for off-grid hydropower become green in the maps of Fig. 1), and the increase in overall population (i.e. more households that demand electricity). The increase between 2040 and 2050 is exclusively due to population growth, since the green area is the same in the two periods.

Similarly, we estimate the maximum expansion of the grid from 2030 onwards by calculating the number of people in the hashed areas in Fig. 1. The approach yields an upper limit for electricity supply from additional expansion of the central grid of 4, 14 and 28 TWh respectively in 2030, 2040 and 2050.

4 Results

On the basis of the residential electricity demand structure in the CENT and SPLIT scenarios, and the constraints we introduced for the deployment of off-grid hydroelectricity generation and additional grid expansion, we let TIAM-ECN determine the underlying least-cost technology mix for the Ethiopian energy system. In Fig. 4, we present our projections for residential electricity generation in our two scenarios, disaggregated into *grid only* (orange bars), *additional grid* (hashed bars) and *off-grid* (green bars). In CENT, electricity can only be accessed through the central grid. In SPLIT, the central grid connects most users until 2030 but from then onwards off-grid options become widespread, providing up to 40% of total residential electricity supply by 2040. We find that the role of additional grid expansion in areas in which affordable *off-grid* options are also available remains small—its contribution, starting at 2% in 2030 and falling below 1% in 2050, is hardly visible in Fig. 4. This indicates that off-grid solutions are more cost-efficient than grid expansion in these regions, under our current cost assumptions.

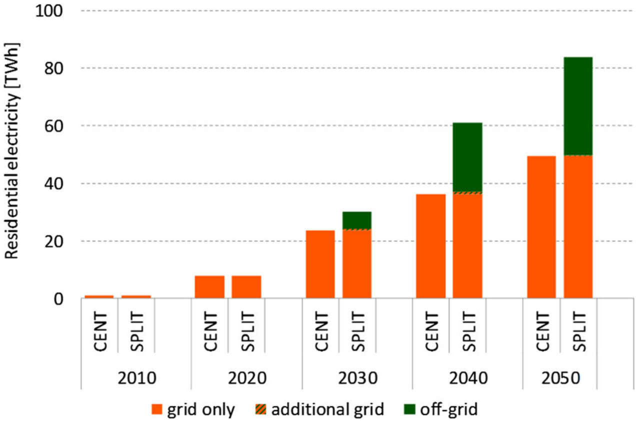


Fig. 4 Residential electricity generation projections in the CENT and SPLIT scenarios

Figure 5 depicts the technology mix underlying *off-grid* electricity generation in the SPLIT scenario from 2030 to 2050. The three bars correspond to the green-coloured segments of Fig. 4. As can be observed in Fig. 5, wind energy dominates the power mix in 2030 and 2040. Solar PV becomes a more affordable substitute in 2050 and thus overtakes wind energy as main electricity provider. The available off-grid hydroelectricity potential is fully exercised at all points in time during the simulated timespan. In the absence of CO_2 mitigation targets, diesel generators remain a viable technology throughout our modelling horizon, although they are not prominent anymore in 2050.

Figure 6 shows projections for total electricity generation in Ethiopia in the CENT and SPLIT scenarios. Until 2050, centralised hydroelectricity production remains the most deployed technology in both scenarios (as described in [29]). From 2040 onwards, electricity from wind and biomass technologies becomes increasingly important, while in 2050, electricity production from wind, biomass and solar PV options taken together overtakes total hydropower generation. During these latter decades, a small role is relegated to fossil fuel-based electricity generation. Figure 6 clearly highlights the effect of additional demand for *off-grid* electricity in the SPLIT scenario by the higher deployment of essentially two technologies, solar panels and wind turbines.

5 Discussion, Conclusions and Recommendations

In this paper, we use GIS data to refine the integrated assessment model TIAM-ECN in order to gain insights in the dynamics of electricity access developments in Ethiopia. We employ existing GIS datasets that map the costs of some of the most promising off-grid energy technologies: solar PV, hydroelectricity and diesel generators. These spatially resolved data provide a detailed representation of technology costs and take into account geographical features such as resource availability. This enables us to project when and where electricity generation technologies may become affordable. Feeding this information into TIAM-ECN, in which we split residential electricity demand into two segments—*grid* and *off-grid*—and take full advantage of its rich technological disaggregation, we analyse the effects induced by increased energy access and the availability of affordable off-grid technologies on the Ethiopian energy system. For this purpose, we enriched the TIAM-ECN input database with a range of off-grid technologies: wind turbines, solar PV modules, hydroelectricity units and diesel generators, each in both its stand-alone and mini-grid format.

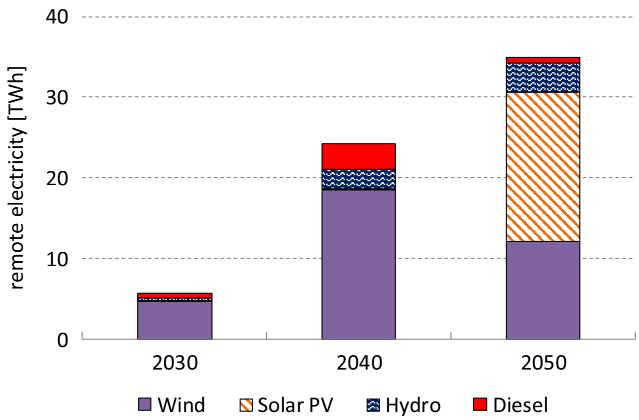
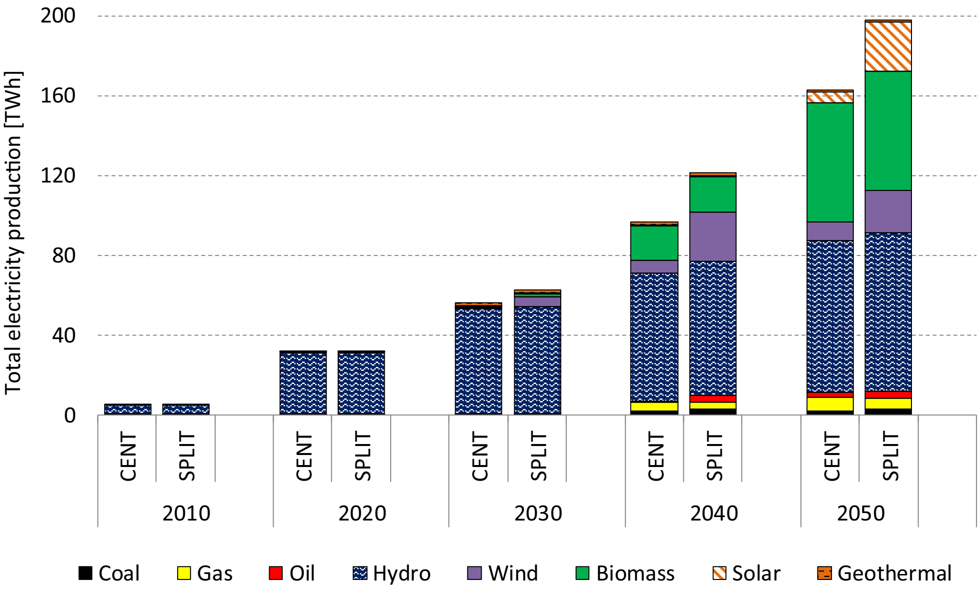


Fig. 5 Breakdown of residential electricity production with off-grid technologies in the SPLIT scenario between 2030 and 2050

Our results demonstrate that by enriching an IAM with information derived from GIS databases, insights are obtained that are different from findings acquired through conventional IAM analysis of energy technology deployment pathways. When duly accounting for the geographical spread in demography and technology costs in Ethiopia, we find that many more people gain access to electricity—especially those living in remote areas—than without considering such spatial detail. The availability of affordable off-grid power production options, based on, e.g. solar and wind energy, that preclude expensive grid connection, is pivotal in increasing energy access. By the middle of the century, off-grid technologies could provide affordable electricity to 70% of the population, based almost entirely on renewable sources such as wind, solar and hydropower. Similar findings are likely to arise in other developing countries as well, which will be the focus of future work. With the TIAM-ECN model, we project universal access to electricity in Ethiopia by 2040. We find that, in the absence of dedicated policy measures, the SDG of reaching universal access by 2030 is unlikely to be met. This important message for policy makers is in line with the results of Dagnachew et al. [3] and Lucas et al. [16] for the whole of Sub-Saharan Africa.

Our methodology to couple GIS data with TIAM-ECN can yield important system-level insights that would be missed with either a traditional IAM analysis, or prior approaches such as in Dagnachew et al. [3], Lucas et al. [16], Mentis et al. [18, 19] and Szabó et al. [23]. An example is the fact that the presence of battery-equipped stand-alone renewable energy technologies in the energy mix lowers the necessity of deploying natural gas-based generation to compensate for intermittency. This effect can be observed by comparing the level of electricity from natural gas in 2050 for the CENT and SPLIT scenarios in Fig. 6. Coupled with a set of policies that limit the use of diesel generators in favour of the deployment of battery-equipped renewable energy-based home systems, this phenomenon could be leveraged on to reduce CO_2 emissions while at the same time increasing energy access. A key novel aspect of our approach is that we use the results of the GIS analysis to determine the demand as well as the

Fig. 6 Total electricity generation projection in the CENT and SPLIT scenarios



maximum potential of grid and off-grid access (Fig. 1), while we project the actual deployment with TIAM-ECN (Figs. 4, 5 and 6), thereby taking into account the linkages with the rest of the energy system as well. Therefore, revenue risks, lock-ins and other effects are treated in a uniform and consistent manner throughout our analysis for all technologies included in our model.

There are multiple ways by which our analysis can be expanded and improved. First of all, our present paper concerns just a case study for Ethiopia, and it would be interesting to extend this research to apply to all of Sub-Saharan Africa. Second, we have focused on only three types of renewable energy options (hydro, wind and solar PV), but many other kinds exist (among which geothermal, biogas and solar thermal). For reasons of completeness, it would be desirable to represent a more diverse set of such off-grid technologies. Third, we have thus far relied and built on existing GIS layers that map out cost variability across a limited set of technologies depending on their locations—namely, solar PV, hydro and diesel. It would be interesting to expand GIS data usage to include other relevant technologies such as wind, geothermal, biomass and solar thermal. Finally, it would be desirable to introduce some realistic limitations on the potential for deployment of mini-grid technologies. In the current set-up—solely based on costs—TIAM-ECN consistently favours mini-grid solutions. Other studies, however, suggest that in many areas, stand-alone technologies may be more suitable, depending on average household consumption levels [3] and on electricity access targets [19]. More in general, overall consumption density and economies of scale are known to be important factors in determining the choice between centralised and off-grid systems. In our analysis, we take these phenomena into account only in an indirect way, since the current grid in Ethiopia already connects the centres with the highest population and electricity consumption density. In future studies, especially for countries in which the central grid is not as developed as in Ethiopia, it may be valuable to consider them as explicit drivers. It should be noted however that in the long term, as the reliability and affordability stand-alone and mini-grid systems increases, it is not so obvious whether economies of scale will lead to the same effects that have been observed so far. In fact, 20 years from now, we might see a reversal of trends even in Europe, where, in spite of the ubiquity of the grid, people may well start to choose for reliable and affordable stand-alone solutions to power their homes.

Further improvements can be made in terms of the way we model energy access in TIAM-ECN; these may provide important lessons for the IAM community. In order to account for the additional grid expansion costs, we take a uniform and constant cost mark-up equal to the WTP in 2030. This is an oversimplification that in most cases renders additional grid expansion less cost-efficient than the deployment of off-grid technologies, and should be subjected to extensive sensitivity analysis, which we leave for future studies. Similarly, costs and other techno-economic parameters of off-grid technologies in TIAM-ECN are taken as averages, valid for an entire country or region. For solar PV, hydro and diesel, when converted into LCOE terms, these costs on average are comparable to those in the LCOE maps. In each single cell of the raster layers, however, LCOEs can differ from those reported in Fig. 3, because the former also take into account local conditions such as capacity factors and fuel prices. As an additional enhancement, one could build into TIAM-ECN a more detailed segmentation for both grid expansion options and off-grid technologies, accounting for local costs and capacity factors, as well as the maximum number of people that could access each segment.

To obtain population maps for the decadal points between 2020 and 2050, we simply projected each cell of the 2010 population layer using total population growth rates from UNDP [27]. This implicitly assumes that the distribution of population across the country remains unaltered over four decades. In reality, between 2010 and 2050, new urban agglomerates can develop, locally changing the population density and hence affecting the way people can access electricity. In order to achieve more realistic projections of population density distribution, in future work, we may attempt to couple the analysis presented in this paper with urban development scenarios. It would also be interesting to elaborate on the distinction between rural and urban areas in our GIS analysis. Since there are considerable differences between rural and urban areas in, among others, GDP, one can expect a significant difference in WTP, which would affect electricity access and technology deployment.

Of course, there are many more ways into which our research can be expanded and improved, which also should be subjected to detailed sensitivity analysis (related, for example to technology cost reductions and fossil fuel prices). These we leave for future studies, by us and the broader energy (access) research community.

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Compliance with Ethical Standards

Disclaimer The contents of this article are the sole responsibility of the authors and can in no way be taken to reflect the views of the European Union or Shell.

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