ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

PERSPECTIVE • **OPEN ACCESS**

Energy access investment, agricultural profitability, and rural development: time for an integrated approach

To cite this article: Giacomo Falchetta 2021 *Environ. Res.: Infrastruct. Sustain.* **1** 033002

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

RECEIVED
21 June 2021

REVISED
13 October 2021

ACCEPTED FOR PUBLICATION
15 October 2021

PUBLISHED
9 November 2021

PERSPECTIVE

Energy access investment, agricultural profitability, and rural development: time for an integrated approach

Giacomo Falchetta*

International Institute for Applied Systems Analysis, Schlossplatz, 1, A-2361, Laxenburg, Austria
Free University of Bozen-Bolzano, Piazza Università 1, 39100, Bolzano, Italy
* Author to whom any correspondence should be addressed.

E-mail: falchetta@iiasa.ac.at

Keywords: energy access, rural development, water–energy–food-economy nexus, private investment, sustainable business models

Abstract

In rural sub-Saharan Africa, the global poverty hotspot, smallholder farmers account for 80% of agricultural production, with 90% of cropland being exclusively rainfed. A key obstacle to rural development and poverty elimination is the lack of electricity access: less than one in three dwellers have electricity at home. The main barrier to rural electrification is the capital-intensiveness of energy supply infrastructure among sparse communities with low demand density and insecurity of payment. While public governments have largely been unable to channel the required resources, private players are often unwilling to pursue risky and unprofitable household electrification programs. In this context, this perspective argues that the paradigm of rural electrification should be centred around an integrated approach aiming at increasing agricultural productivity and profitability. These bear the necessary potential to enable local income generation and thus also provide an incentive for private energy investment, including in the residential sector. A framework for the integrated approach is proposed and the crucial synergetic role of data modelling and business and policy research to pursue this paradigm is discussed.

1. Introduction

In sub-Saharan Africa (SSA) 80% of agricultural production comes from smallholder farmers [1]. Extensive rain-fed agriculture accounts for more than 90% of agricultural land [2]. Unpredictable and erratic rainfall patterns are therefore a leading cause of low agricultural productivity [3–5]. The low degree of mechanisation in the sector has been further exacerbating this condition [6], which results in cyclical famines, persistent poverty traps, and limited local development opportunities [7].

The precarious situation of the African agriculture system is even more pressing if considered against the backdrop of other important trends and development gaps in rural areas of the region, summarised in figure 1. The numbers, presented both in absolute and normalised terms (i.e., divided by their level in the baseline year 2000), show: (i) the increasing demographic pressure, with the rural population having grown from 450 to over 650 million over the last 20 years [8]; (ii) the large electricity access gap, with the rural electrification level at about 30% irrespective of recent progress [9–11]; (iii) the relevance of agricultural land use: >40% of the land in the region is devoted to agriculture, with the figure still growing [12]; (iv) the increasing water stress, with per-capita freshwater resources having declined by about 40% in less than 20 years [13]; and (v) the fact that more than one in six sub-Saharan Africans living without sufficient nourishment [12], with the indicator having stagnated over the last years.

To tackle these and other poverty and development gaps in rural SSA, there is urgent need for an agricultural transformation [14] to ensure more stable yields and increased agricultural profitability for the millions of rural dwellers living in poverty who practice subsistence agriculture and are subject to food insecurity [15, 16]. Electricity is a crucial input required to initiate this transition [14, 17] because it enables artificial irrigation through water pumping—which can ensure that crops' evapotranspiration needs are met [18]—and mechanical crop processing, which can add significant economic value to the local yield [19] and thus increase farmers' income [17, 20]. Banerjee *et al* estimate that by 2030 electricity demand from agriculture for both

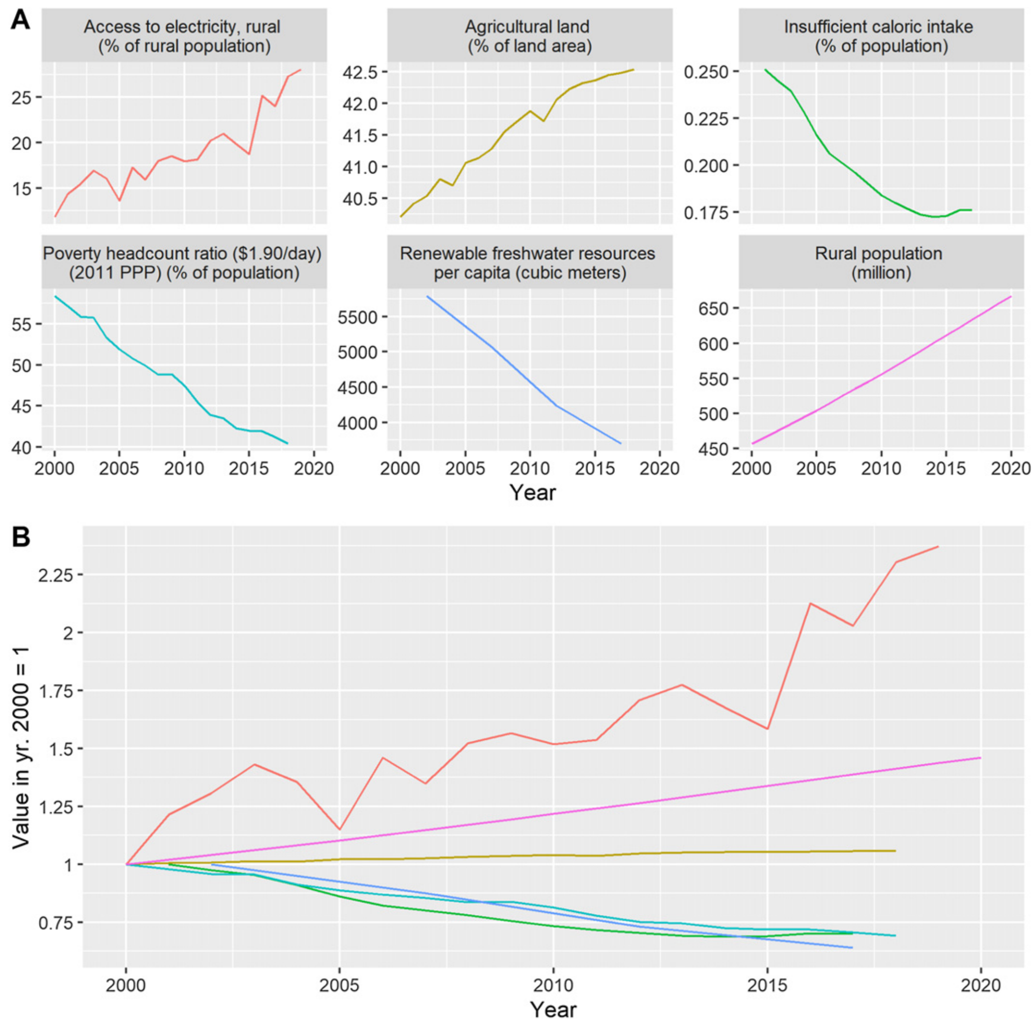

Figure 1. Evolution of selected water–energy–agriculture–economy indicators in SSA. (A) Absolute values; (B) normalised indicators (year 2000 = 1). The normalised indicators are interpreted e.g., as a doubling of the indicator initial value if the variable takes value 2, or as a halving of the initial value if the variable takes value −1. Data sources: [12, 21].

irrigation and milling in SSA could double from current levels if rainfed areas with economic potential would be equipped for irrigation, reaching about 9 GW [20].

However, bringing electricity to sparsely populated, poor rural areas has so far proved challenging [11, 22]. The key barrier to household electrification programs is the low profitability and risky nature of rural electrification investment for private investors [23, 24]. While governments simply lack the means to expand the national grid into remote communities with low energy demand density, private players have been struggling to find the economic incentive to develop decentralised electricity generation and distribution investments [25–27]. Electrification programs (and energy access development indicators such as SDG 7) have mostly been prioritising the residential sector, an approach which has nevertheless struggled to prove financially sustainable.

Only recently have some governments devoted specific attention to opportunities for electrification in agriculture. A relevant example is the 'Access to Distributed Electricity and Lighting in Ethiopia' project [28], which was funded by the World Bank in 2021. The project also has a strong focus on closing the gender gap in the energy sector and increasing the percentage of women participating in the mini-grid sector and off-grid technology value chain. Another recent large-scale program in this direction is the Yeleen Rural Electrification Project in Burkina Faso [29], approved by the Green Climate fund in 2018 and devoting specific focus to productive users in rural areas. Within the scope of this project, micro-finance institutions are encouraged to provide loans to productive users in the areas where solar mini-grids will be installed.

In this context, this perspective argues that the rural electrification paradigm should be centred around an integrated approach aiming at increasing agricultural productivity and profitability, rather than directly targeting residential electrification. Agricultural transformation bears significant potential both to enable local income generation and provide the necessary incentive and guarantees for private investment in energy access, including in the residential sector [30]. The idea of an integrated energy–agriculture–economy approach to rural development has been gaining significant momentum in recent years, along with the role of anchor customers in energy access investments [22, 31]. Within the scope of this paper, rural development is defined as a strategy designed to improve the economic and social life of the rural poor [32]. Such strategy relies on the installation of infrastructure and the creation of local knowledge that can promote an economically and environmentally sustainable improvement of development indicators.

Several studies have proposed the adoption of new paradigms focussed on agricultural transformation through the input of energy and water technologies to initiate rural development. For instance, Shirley [33] explores the interactions between agriculture, energy, economy, trade, climate resilience, and livelihoods across SSA, describing the opportunities for an intersectional approach to interventions at the food–energy nexus. In addition, Shirley [34] develops recommendations to support smallholder access to value-addition supply chains in Africa proposing reforms of smallholder farmer cooperatives to ensure increased bargaining power, encouraging a rapid and targeted deployment of mini-grids in village communities engaged in staple and cash crop farming, and fostering the creation of incentives to increase access to micro- and commercial finance for farmers and cooperatives. Xie *et al* [35] develop a joint irrigation-energy planning framework to estimate how much of the potential irrigated area could be powered with standalone solar photovoltaic (PV) energy. Banerjee *et al* [20] highlight that the agribusiness sector requires electricity to grow to its potential, while the expansion of rural energy services needs consumers with consistent power needs to serve as a reliable revenue source, potentially generating a potential double dividend. Finally, Lefore *et al* [36] introduce a framework to inform sustainable and inclusive solar irrigation, emphasizing the need for an understanding of how solar irrigation can be scaled to be both accessible for smallholder farmers and environmentally sustainable.

Yet, a contribution 'putting the pieces together', i.e., providing an integrated framework linking electricity access investment and rural development with specific attention to the crucial synergetic role of data and modelling and innovative business and policy models research has so far been missing. Moreover, a focus on both sides of the feedback loop, namely (i) energy as an enabler of agricultural productivity and profitability growth, and (ii) agriculture as a channel to ensure the financial sustainability of energy access investments, is pivotal.

2. Overlapping agriculture–energy–economy gaps: time for an integrated approach

A crucial aspect relative to the water–energy–economy gaps in SSA is their degree of geographical overlap. As seen from figure 2, areas characterised by a high density of rainfed cropland, electricity access deficit and low relative (i.e., with respect to the national level) wealth tend to coincide. The plotted data are derived from [37] for the distribution of rainfed cropland, [10] for the electricity access deficit and [38] for non-conventional spatially-explicit estimates of wealth, all representing recent databases created with the support of satellite imagery that allow for a timely understanding of development gaps and structural change dynamics over space.

It is relevant to highlight that across large areas e.g., West Africa (and most notably Nigeria), Ethiopia, riparian countries of Lake Victoria, Tanzania, Mozambique, Zimbabwe, and Madagascar a large overlap of rainfed cropland, electricity access deficit, and economic deprivation is observed. These maps have the benefit of providing a first-order sense of the interconnectedness of the agriculture–energy–economic deprivation. Given the concomitant and overlapping nature of the poverty, energy access, agricultural profitability, food security, and overall rural development challenges, an integrated approach is thus necessary to elaborate sustainable solutions. On the other hand, it must be remarked that the energy–agriculture–development nexus is a highly complex one, and thus that this geographic correlation does not automatically ensure linear dynamics of causality until further investigation [39].

In this context, figure 3 proposes a framework to leverage the geographical overlap of agriculture–energy–economy gaps and enable rural development. The framework was developed building on recent literature contributions that connect techno-economic and financial considerations to the challenge of rural energy access infrastructure investment [30, 40].

The flowchart shows the mechanism behind the argument that the rural electrification paradigm should be centred around an integrated approach aiming at increasing agricultural productivity and profitability, rather than on the conventional '*household electrification first*' paradigm. Increasing farmers' income locally bears in fact significant potential both to enable rural development and to provide the necessary incentive and guarantees for private investment in energy access, including in the less profitable sectors such as the residential and educational ones.

The proposed mechanism builds on the following: the provision of electricity through decentralised systems such as standalone PV systems (with or without storage) or RE-based (such as biomass, PV, wind, or hydro-powered) mini-grids can enable on-demand surface water or groundwater pumping [41] to access sources of blue water when green water (i.e. rain) is insufficient and crops would undergo water stress. Crop stress results in fact in reduced yield and lower product quality. This is even more relevant under the expected

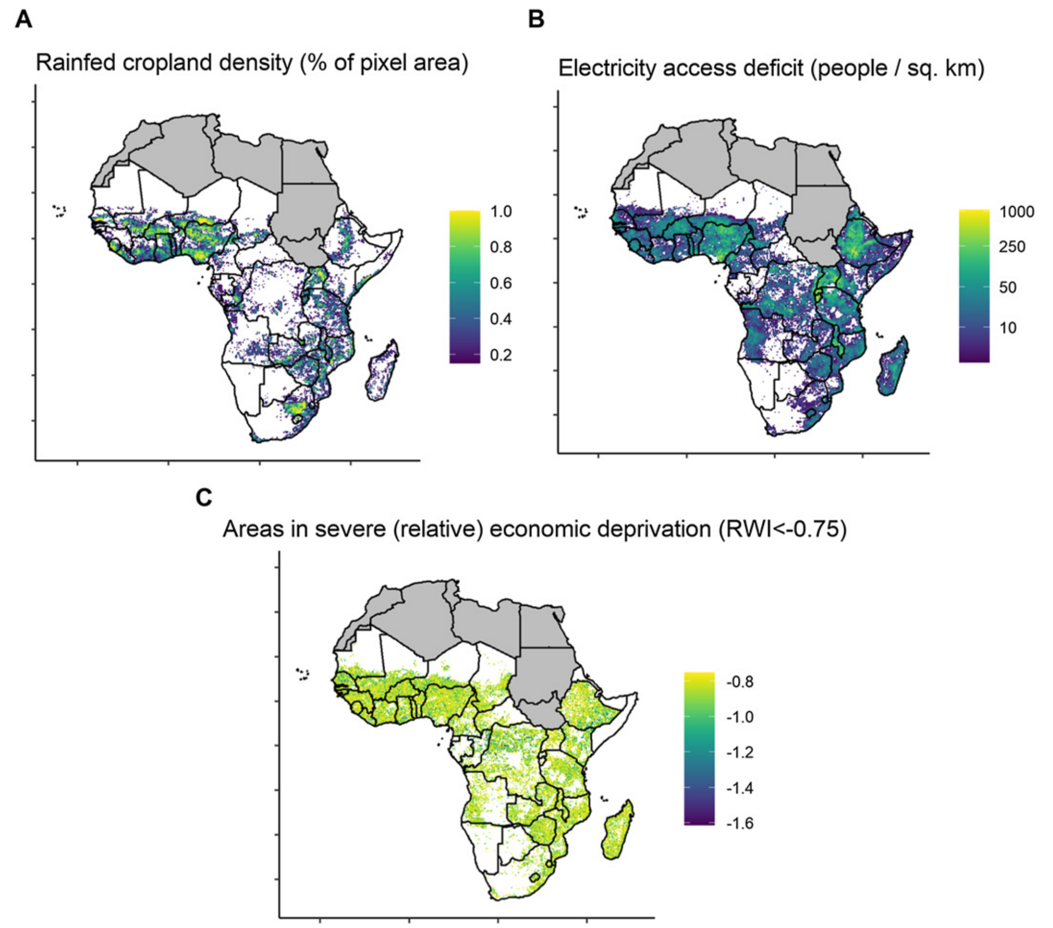

Figure 2. High-resolution data of (A) rainfed portion of cropland; (B) density of population without electricity access; (C) areas with low relative wealth index. Countries filled in grey identify countries with missing data or outside SSA.

negative impacts of climate change on crop yields [42, 43]. In particular, sustainable irrigation expansion is an important adaptation strategy to climate change and can make crop production more resilient while increasing crop yields. Recent work has assessed the potential for sustainable irrigation expansion over croplands facing 'agricultural economic water scarcity' [44, 45], or croplands where water is available for irrigation in rivers and lakes but irrigation is not in place for socio-economic barriers. This research showed that SSA is the region with the greatest potential for irrigation expansion under current and warmer climate conditions [46].

In parallel, post-harvesting crop processing activities such as milling a could (at least in part) be carried out in proximity of the farming site (e.g., by local smallholder consortia that co-own mechanical processing machinery) to retain a greater share of the value of the final retail price. In fact, beyond meeting subsistence needs, smallholder farmers usually sell their crops raw at wholesale markets at low prices [1], where large (often international) corporation purchase them in bulk and sell the processed products at significantly higher prices.

As a result of both the larger and more stable crop yields thanks to artificial irrigation and of the increased per-unit profitability thanks to the local processing, several positive outcomes could materialize. These include a considerable push to most development indicators, and chiefly a lower risk of food insecurity, but also an increased income generation potential. While substantial uncertainty persists over the welfare impacts of electrification [47], there is evidence of the positive effect of electricity provision on time spent by household members in income-generating activities [48–51]. Provided a set of conditions is satisfied, this can provide the spark for infrastructure investment and technological change that in the long-run might onset structural change dynamics [39], such as the rise of the secondary and tertiary sectors among communities currently dependent solely on the agricultural sector as their income source [52]. Gender and education (including capacity building) play an important role in this nexus, both as drivers of the transition and as potential areas of positive impact [53]. Finally, a co-benefit of increased agricultural profitability is that smallholder farmers could become less sensible to increasing pressure for large scale land acquisition driven by large private groups, which are surging in SSA [54] and have potentially detrimental effects for food security [55].

In turn, a more profitable agricultural sector thanks to the input of electric energy can provide the sufficient incentive and security of payment from electricity beneficiaries to private energy access system developers [30].

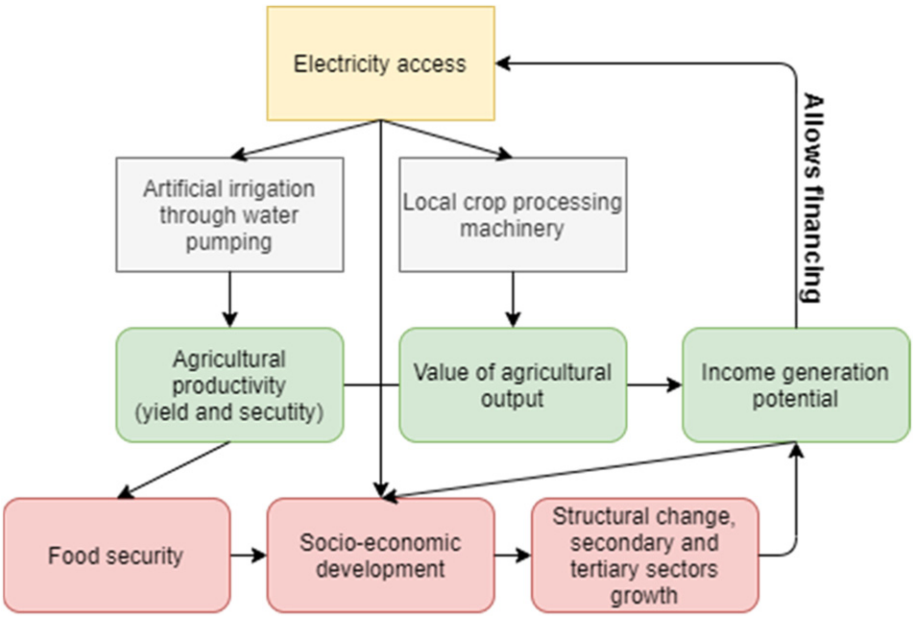

Figure 3. Framework of the proposed energy access, agricultural profitability, and rural development integrated approach.

The realization of this positive feedback loop is however subject to specific business, technology and policy conditions [56]. In our opinion, the keyword is conditionality, namely the development of business models that are based on the installation of electricity supply systems conditional on local farmers using (at least part of) this energy for well-defined agricultural purposes. Namely, contracts should be designed aligning instalment payments with crop yield seasons, while also providing insurance mechanisms against adverse events, such as floods or pests [57]. These issues are discussed in greater detail in section 4.

3. Data and modelling: current status and future opportunities

Data-driven modelling studies bear a crucial role in providing public and private decision makers with the sufficient information and confidence in pursuing new, energy-driven rural development paradigms, policies, and business models.

Relevant examples include the creation and analysis of recent, high-resolution data on current cropping (the extent of cultivated land by crop type, irrigation technology, additional inputs such as fertilizers, and farming practices, as well as of yield levels and the yield gap) [58]. In parallel, an assessment of potential shifts in cropping patterns would be highly relevant for agrarian decision-makers: for instance, to identify strategies to maximise local crop profitability for farmers while guaranteeing that universal food security objectives are in reach and the '*food* vs. *income*' trade-off is minimized [59].

Another very important aspect to be investigated concerns the identification of sustainability boundaries in the context of agricultural transformation. This includes ensuring that environmental flows are preserved at sustainable levels when planning new irrigation schemes [60], such as groundwater withdrawals during the growing season, and that land is not overused, both at the intensive and the extensive margin.

Increasing productivity through irrigation presents own problems and potential solutions, which are suitable to be analysed in data-driven contexts [18] by agricultural and environmental scientists. Context-specific infrastructure, e.g., the choice of the optimal irrigation system, need to be carefully addressed before promoting large-scale policies aimed at fostering the agricultural sector [61].

The question of what electricity generation and distribution solutions are more suitable at each settlement and the surrounding agricultural land in another crucial one. While important work has been already carried out for the residential sector [62, 63], there is an important literature gap when it comes to evaluating the relevance of the agricultural sector demand in determining optimal system design, investment requirements, and financing schemes [35, 64]. The open questions relate both to the trade-off between the expansion of the national grid and the development of decentralised solutions [65] and—in the latter case—the choice of the most suitable scale (from solar pumps to mini-grids) and generation and storage systems.

Energy supply investment requirements and costs is directly linked with the need to estimate the potential local gains from increased agricultural productivity and mechanisation, namely evaluating if and where an agriculture transformation could really turn out to be profitable in the longer-run for both the local community and for project developers [64]. Recently, commercial research initiatives have turned their attention exactly in this direction (e.g., *villagedata.io*), but we argue that there is the need for more openly accessible research in this sense.

An even more daunting question, calling for complex system analysts and scientists, concerns the identification of the turning points to onset structural change in rural areas, namely the agricultural, socio-economic, and environmental thresholds that need to be achieved to ensure that structural economic change occurs in rural areas [39]. This encompasses the creation of secondary and tertiary sectors economic activities, the creation of new and more qualified employment, and ultimately a new socio-economic structure that can ensure the needs of the community and guarantee sustainable economic growth.

4. Business model and policy implications

While data-driven research is crucial, investigation into business and policy solutions to operationalise the findings on scientific research is equally important in the context of unleashing energy access investment targeted at rural development. Among the main barriers faced by providers of decentralised electricity generation and distribution systems in rural areas, there lie in fact issues of both collective nature, such as economic sustainability under a low demand (and thus limited profit potential) and free riding, and challenges related to the regularity of payments from individual private investors, e.g. households and small-scale activities [22, 66–68].

Very high discount rates from local electricity supply systems developers are the consequence of the large degree of risk incurred from the demand-side and from poor sectoral regulation and policy uncertainty [23]. High discount rates create a negative feedback loop, as they raise the cost of capital and therefore discourage individual households and activities themselves to make upfront payments for infrastructure or create substantial struggle to pay regular instalments. These issues are responsible for a large part of the obstacles encountered by the standalone energy access sector over the last decades [66].

While new business models, such as 'pay as you go', are aimed at mitigating this type of issues [69], to ensure profitability of the sector in rural areas and thus mass uptake of decentralised solutions business solutions must be able to explicitly consider the energy–development–agriculture nexus that is found in rural areas (i.e. where standalone solutions bear the greatest potential according to techno-economic electrification modelling studies). Recent studies have explored this business model paradigm shift. For instance, Kyriakarakos *et al* [30] show how a community of households owning agricultural land or working in the fields could meet the high cost of rural electrification through the increased value of locally produced products thanks to energy-enabled artificial irrigation and crop processing, and thus cross-subsidize the cost of household electrification.

On an ethical level universal access to modern energy should be considered a fundamental right [70, 71]. Nonetheless, in rural communities living in energy poverty and without near-term possibility of being reached by the state-owned central grid, it is crucial to identify agrobusiness-centred models that are able to ensure profitability and risk reduction for profit-seeking private providers of decentralised energy access solutions. Namely, business models that aim at lowering discount rates and provide advantageous pricing schemes conditional on the purchaser (i.e., smallholder farmer and/or small-scale commercial activities) committing to using part of this energy for income-generating activities, i.e., not limiting use to household basic needs.

While potentially a broad range of income-generating energy uses fall under this umbrella, including non-agricultural activities e.g., handcrafting, barber shops, welding, online jobs, we argue that the focal point should build on agricultural activities, also due to the spatial overlaps highlighted in figure 2. Business models inclusive of conditionality of supply based on energy use for increasing cropland productivity through water pumping for irrigation and crop processing for increasing the added value and thus the revenue of the yield can act as a trigger to climb the energy ladder in other sectors and with higher consumption levels as income grows and more appliances are purchased [72].

A complementary key condition is ensuring that decentralized energy access solutions are purchased and installed in combination with appliances that enable those income-generating energy uses [73]. It is in this sense that developers should sell bundles including e.g., a solar home system and an appliance with productive use potential such as a water pump and the required pipes equipment.

Along with the private players, the policymakers have an important role to play in enabling this type of business models. On the one hand, effective regulatory reform is required in contexts where structural institutional, political and financial risks discourage private and foreign investment [23, 74]. On the other hand, insurance instruments should be offered to farmers investing in productive energy access systems so that they can hedge against environmental (e.g., floods, pests, insects) and economic (e.g., international price volatility) shocks. In other word, public policymakers seeking to achieve rural development and achieving universal household electrification should pursue an integrated energy–agriculture policy that can unleash the strong interdependencies between energy access investment, agricultural profitability, and rural development.

5. Conclusions

This perspective article argues that it is urgent to concentrate efforts towards the realisation of an integrated approach to energy access investment, agricultural productivity, and rural development. Not only is energy required for boosting agricultural productivity and enable structural change in the labour sector and in socio-economic outcomes among rural poor communities, but also a source of regular and growing income like the energy-boosted agricultural output is required to attract private providers of energy access solutions and allow them designing financially sustainable business models.

In this context, an integrated effort between nexus modelling research and business model experts is required. Modelling research helps the development of decision support tools that facilitate and streamline some of the costliest processes in the implementation of energy access business models: the process of site selection and technology evaluation. The modelling must be able to adapt to the local contexts and leverage on the growing availability of high spatio-temporal resolution data. The modelling work should however be complemented by research into the local market and sector conditions to ensure local relevance, i.e., through focus groups, interviews, rural communities assessments, policy structures evaluation, and by assembling and collating data and eventually testing solutions. This is crucial for the macro, national government-level regulatory perspective, via the energy access funding and investment landscape to the very micro validation of community-level business models.

The research agenda should thus focus on providing a replicable and scalable modelling infrastructure and business approach which will exert a tangible impact on the livelihoods of farmers and their broader communities across Africa.

This perspective article has sought to connect the dots between energy access investment, agricultural profitability, and rural development by examining crucial water–energy–food–development nexus indicators and proposing an integrated approach. Yet, it must be remarked that causality is not immediate among the issues investigated, as complex dynamics dominate those interactions [39]. Rigorous ex-post evaluations are crucial to quantify the strength and direction of such interactions in different contexts.

As a final remark, it should be noted that this article is not intended to discourage household electrification, which remains a crucial target and a necessary condition for enabling energy services such as lighting, refrigeration, and air circulation and cooling [75]. On the contrary, the discussed paradigm is relevant in the widespread context of lack of financial capacity from public electrification infrastructure developers and lack of incentive for private energy access system providers to directly target rural households.

Acknowledgments

Financial support from the European Commission H2020 funded project LEAP-RE (Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy), Grant Number 963530, is gratefully acknowledged.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare no competing financial interests.

ORCID iDs

Giacomo Falchetta https://orcid.org/0000-0003-2607-2195

References

[1] Harris T and Consulting T H 2014 *Africa Agriculture Status Report 2014: Climate Change and Smallholder Agriculture in sub-Saharan Africa* Alliance for a Green Revolution in Africa (AGRA)

[2] Wani S P, Rockström J and Oweis T Y 2009 *Rainfed Agriculture: Unlocking the Potential* (*Comprehensive Assessment of Water Management in Agriculture Series* vol 7) (CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI)) p 310

[3] Ward P S, Florax R J G M and Flores-Lagunes A 2014 Climate change and agricultural productivity in sub-Saharan Africa: a spatial sample selection model *Eur. Rev. Agric. Econ.* **41** 199–226

[4] Mechiche-Alami A and Abdi A M 2020 Agricultural productivity in relation to climate and cropland management in West Africa *Sci. Rep.* **10** 3393

[5] van Ittersum M K *et al* 2016 Can sub-Saharan Africa feed itself? *Proc. Natl Acad. Sci. USA* **113** 4964–14969

[6] Gumbe L O 2020 Agricultural mechanisation for modernisation of African agriculture *2020 ASABE Annu. Int. Virtual Meet.* (American Society of Agricultural and Biological Engineers)

[7] Osabohien R, Matthew O, Gershon O, Ogunbiyi T and Nwosu E 2019 Agriculture development, employment generation and poverty reduction in West Africa *Open Agric.* J **13** 82–9

[8] United Nations, Department of Economic and Social Affairs 2017 *World Population Prospects: the Revision* (N Y: Popul. Div. Dep. Econ. Soc. Aff. U N Secr.)

[9] IEA, IRENA, United Nations Statistics Division 2020 *Tracking SDG7: the Energy Progress Report 2020*

[10] Falchetta G, Pachauri S, Parkinson S and Byers E 2019 A high-resolution gridded dataset to assess electrification in sub-Saharan Africa *Sci. Data* **6** 1–9

[11] Falchetta G, Pachauri S, Byers E, Danylo O and Parkinson S C 2020 Satellite observations reveal inequalities in the progress and effectiveness of recent electrification in sub-Saharan Africa *One Earth* **2** 364–79

[12] FAO 2017 FAOSTAT database food agric. Organ U N http://www.fao.org/faostat/en/#data

[13] FAO 2005 AQUASTAT F. AQUASTAT database http://www.fao.org/nr/water/aquastat/

[14] Rosa L *et al* 2021 Energy implications of the 21st century agrarian transition *Nat. Commun.* **12** 2319

[15] Dzanku F M, Jirström M and Marstorp H 2015 Yield gap-based poverty gaps in rural sub-Saharan Africa *World Dev.* **67** 336–62

[16] Fraval S *et al* 2019 Food access deficiencies in sub-Saharan Africa: prevalence and implications for agricultural interventions *Front. Sustain. Food Syst.* **3** 104

[17] Best S 2014 *Growing Power: Exploring Energy Needs in Smallholder Agriculture Int. Inst. Environ. Dev. IIED Discuss Paper* (London UK: IIED)

[18] Mashnik D, Jacobus H, Barghouth A, Jiayu Wang E, Blanchard J and Shelby R 2017 Increasing productivity through irrigation: problems and solutions implemented in Africa and Asia *Sustain. Energy Technol. Assess.* **22** 220–7

[19] Sims B and Kienzle J 2016 Making mechanization accessible to smallholder farmers in sub-Saharan Africa *Environments* **3** 11

[20] Banerjee S G, Malik K, Tipping A, Besnard J and Nash J 2017 *Double Dividend: Power and Agriculture Nexus in sub-Saharan Africa* (World Bank)

[21] World Bank 2019 World Bank data https://data.worldbank.org/ (accessed 3 March 2018)

[22] Peters J, Sievert M and Toman M A 2019 Rural electrification through mini-grids: challenges ahead *Energy Policy* **132** 27–31

[23] Falchetta G, Dagnachew A G, Hof A F and Milne D J 2021 The role of regulatory, market and governance risk for electricity access investment in sub-Saharan Africa *Energy Sustain. Dev.* **62** 136–50

[24] Williams N J, Jaramillo P, Taneja J and Ustun T S 2015 Enabling private sector investment in microgrid-based rural electrification in developing countries: a review *Renew. Sustain. Energy Rev.* **52** 1268–81

[25] Ikejemba E C X, Mpuan P B, Schuur P C and Van Hillegersberg J 2017 The empirical reality & sustainable management failures of renewable energy projects in sub-Saharan Africa (part 1 of 2) *Renew. Energy* **102** 234–40

[26] Ikejemba E C X, Schuur P C, Van Hillegersberg J and Mpuan P B 2017 Failures & generic recommendations towards the sustainable management of renewable energy projects in sub-Saharan Africa (part 2 of 2) *Renew. Energy* **113** 639–47

[27] Okereke O C 2017 *Causes of failure and abandonment of projects and project deliverables in Africa* vol 6 (PM World J) pp 1–16

[28] The World Bank 2021 Development projects: access to distributed electricity and lighting in Ethiopia (ADELE)—P171742 World Bank n.d. https://projects.worldbank.org/en/projects-operations/project-detail/P171742 (accessed 4 October 2021)

[29] Green Climate Fund 2018 Fund G C. FP093: Yeleen rural electrification project in Burkina Faso https://greenclimate.fund/project/fp093 (accessed 4 October 2021)

[30] Kyriakarakos G, Balafoutis A T and Bochtis D 2020 Proposing a paradigm shift in rural electrification investments in sub-Saharan Africa through agriculture *Sustainability* **12** 3096

[31] Robert F C, Sisodia G S and Gopalan S 2017 The critical role of anchor customers in rural microgrids: impact of load factor on energy cost *2017 Int. Conf. Comput. Power Energy Inf. Commuincation ICCPEIC* (Piscataway, NJ: IEEE) pp 398–403

[32] Takeuchi S and Marara I J 2016 *African Studies and Rural Development*

[33] Shirley R 2021 Energy for food, livelihoods, and resilience: an integrated development agenda for Africa *One Earth* **4** 478–81

[34] Shirley R 2020 *Powering agriculture: Unlocking Africa's Next green Revolution*

[35] Xie H, Ringler C and Mondal M A H 2021 Solar or diesel: a comparison of costs for groundwater-fed irrigation in sub-Saharan Africa under two energy solutions *Earths Future* **9** e2020EF001611

[36] Lefore N, Closas A and Schmitter P 2021 Solar for all: a framework to deliver inclusive and environmentally sustainable solar irrigation for smallholder agriculture *Energy Policy* **154** 112313

[37] Thenkabail P 2016 *Global Food Security Support Analysis Data (GFSAD) Crop Dominance 2010 Global 1 km V001*

[38] Chi G, Fang H, Chatterjee S and Blumenstock J E 2021 Micro-estimates of wealth for all low- and middle-income countries (arXiv:210407761) Cs Econ Q-Fin

[39] Riva F, Ahlborg H, Hartvigsson E, Pachauri S and Colombo E 2018 Electricity access and rural development: review of complex socio-economic dynamics and causal diagrams for more appropriate energy modelling *Energy Sustain. Dev.* **43** 203–23

[40] Michoud B and Hafner M 2021 *Financing Clean Energy Access in sub-Saharan Africa: Risk Mitigation Strategies and Innovative Financing Structures* (Berlin: Springer)

[41] IEA 2017 *WEO 2017 Special Report: Energy Access Outlook* International Energy Agency

[42] Blanc E 2012 The impact of climate change on crop yields in Sub-Saharan Africa *J. Clim. Change* **01** 1–13

[43] Müller C *et al* 2021 Exploring uncertainties in global crop yield projections in a large ensemble of crop models and CMIP5 and CMIP6 climate scenarios *Environ. Res. Lett.* **16** 034040

[44] You L Z 2008 *Africa: Irrigation Investment Needs in Sub-saharan Africa* (Washington, DC: World Bank)

[45] You L *et al* 2009 Torrents and trickles: irrigation spending needs in Africa *AICD Backgr Pap.*

[46] Rosa L, Chiarelli D D, Sangiorgio M, Beltran-Peña A A, Rulli M C, D'Odorico P and Fung I 2020 Potential for sustainable irrigation expansion in a 3 °C warmer climate *Proc. Natl Acad. Sci. USA* **117** 29526–34

[47] Urpelainen J 2019 The quest for impact in household electrification: we still Roam in the dark|ISEP n.d. https://sais-isep.org/blog/the-quest-for-impact-in-household-electrification-we-still-roam-in-the-dark (accessed 26 November 2019)

[48] Bernard T 2010 Impact analysis of rural electrification projects in sub-Saharan Africa *World Bank Res. Obser.* **27** 33–51

[49] Bos K, Chaplin D and Mamun A 2018 Benefits and challenges of expanding grid electricity in Africa: a review of rigorous evidence on household impacts in developing countries *Energy Sustain. Dev.* **44** 64–77

[50] Rathi S S and Vermaak C 2017 The impacts of rural electrification on labour market outcomes in developing countries: evidence from India and South Africa *Pap. Present ESSA 2017 Bienn Conf.* (RHODES Univ. Grahamst)

[51] Van de Walle D P, Ravallion M, Mendiratta V and Koolwal G B 2013 *Long-Term Impacts of Household Electrification in Rural India*

[52] Peters J and Sievert M 2016 Impacts of rural electrification revisited—the African context *J. Dev. Effect.* **8** 327–45

[53] Graves A, Rosa L, Nouhou A M, Maina F and Adoum D 2019 Avert catastrophe now in Africa's Sahel *Nature* **575** 282–6

[54] Hall R 2011 Land grabbing in Africa and the new politics of food *Future Agric. Policy Brief*

[55] Müller M F *et al* 2021 Impact of transnational land acquisitions on local food security and dietary diversity *Proc. Natl Acad. Sci.* **118** e2020535118

[56] Zadawa A N and Omran A 2020 Rural development in Africa: challenges and opportunities *Sustaining Our Environment for Better Future: Challenges Opporunities* ed ed A Omran and O Schwarz-Herion (Berlin: Springer) pp 33–42

[57] Merrey D J and Lefore N 2018 *Improving the Availability and Effectiveness of Rural and 'Micro' Finance for Small-Scale Irrigation in sub-Saharan Africa: A Review of Lessons Learned*

[58] International Food Policy Research Institute 2020 *Spatially-disaggregated crop production Statistics data in Africa South of the Sahara for 2017*

[59] Davis K F, Rulli M C, Seveso A and D'Odorico P 2017 Increased food production and reduced water use through optimized crop distribution *Nat. Geosci.* **10** 919–24

[60] Mabhaudhi T, Mpandeli S, Nhamo L, Chimonyo V, Nhemachena C, Senzanje A, Naidoo D and Modi A 2018 Prospects for improving irrigated agriculture in southern Africa: linking water, energy and food *Water* **10** 1881

[61] Higginbottom T P, Adhikari R, Dimova R, Redicker S and Foster T 2021 Performance of large-scale irrigation projects in sub-Saharan Africa *Nat. Sustain.* **4** 501–8

[62] Mentis D *et al* 2017 Lighting the World: the first application of an open source, spatial electrification tool (OnSSET) on sub-Saharan Africa *Environ. Res. Lett.* **12** 085003

[63] Szabó S, Bódis K, Huld T and Moner-Girona M 2011 Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension *Environ. Res. Lett.* **6** 034002

[64] Falchetta G, Stevanato N, Moner-Girona M, Mazzoni D, Colombo E and Hafner M 2021 The M-LED platform: advancing electricity demand assessment for communities living in energy poverty *Environ. Res. Lett.* **16** 074038

[65] Deichmann U, Meisner C, Murray S and Wheeler D 2011 The economics of renewable energy expansion in rural sub-Saharan Africa *Energy Policy* **39** 215–27

[66] Bhattacharyya S C 2013 Financing energy access and off-grid electrification: a review of status, options and challenges *Renew. Sustain. Energy Rev.* **20** 462–72

[67] Gregory J and Sovacool B K 2019 The financial risks and barriers to electricity infrastructure in Kenya, Tanzania, and Mozambique: a critical and systematic review of the academic literature *Energy Policy* **125** 145–53

[68] Sweerts B, Longa F D and van der Zwaan B 2019 Financial de-risking to unlock Africa's renewable energy potential *Renew. Sustain. Energy Rev.* **102** 75–82

[69] Mazzoni D 2019 *Digitalization for energy Access in sub-Saharan Africa: Challenges, Opportunities and Potential Business Models*

[70] Kondongwe S 2019 Access to universal modern energy services as a basic human right: a critical analysis *Social Science Research Network* (Rochester, NY)

[71] Löfquist L 2020 Is there a universal human right to electricity? *Int. J. Human Rights* **24** 711–23

[72] Chattopadhyay D, Bazilian M and Lilienthal P 2015 More power, less cost: transitioning up the solar energy ladder from home systems to mini-grids *Electr. J.* **28** 41–50

[73] Taneja J 2018 If you build it, will they Consume? Key challenges for universal, reliable, and low-cost electricity Delivery in Kenya *Cent. Glob. Dev. Work Pap.*

[74] Hafner M, Tagliapietra S and de Strasser L 2018 *Energy in Africa: Challenges and Opportunities* (Berlin: Springer)

[75] Falchetta G and Mistry M N 2021 The role of residential air circulation and cooling demand for electrification planning: implications of climate change in sub-Saharan Africa *Energy Econ.* **99** 105307