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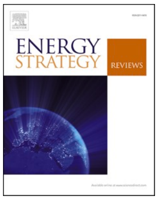

A renewable energy-centred research agenda for planning and financing Nexus development objectives in rural sub-Saharan Africa

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ABSTRACT

In rural sub-Saharan Africa – the global poverty hotspot – the vast majority of cropland is rainfed only, resulting in reduced and unstable yields. Smallholder farmers account for 80% of agricultural production but they have limited access to relevant services to support both commercial operations and their livelihoods: more than two-thirds of rural dwellers have no access to electricity (crucial for crop irrigation, processing, and storage) and about 40% have no access to clean water. Previous research has analysed integrated technological and resource management approaches to tackle these overlapping development gaps. To finance and implement such transformations in resource-constrained settings, it is now crucial to understand the business and investment implications, also considering the strong regional population growth and the increasing frequency and intensity of climate extremes. Here, we lay out a research agenda that promotes the integration of multi-scale modelling excellence along the climate-water-renewable energy-agriculture-development Nexus and the creation of robust business models for private companies that can sustainably support private smallholder farmers of SSAin their effort to eradicate poverty and inequality. The proposed agenda is a cornerstone of the EC-H2020 project LEAP-RE RE4AFAGRI ("*Renewable Energy for African Agriculture: Integrating Modelling Excellence and Robust Business Models*"). In proposing the agenda, we highlight the importance of integrating energy access into the Nexus framework from both research and investment perspectives.

1. Introduction

Agriculture has a strong potential for growth in Africa: according to the World Bank, the regional agricultural sector will be worth one trillion dollars by 2030 [1], whilst the continent's food production is expected to grow as much as by 60% by 2050 [2]. However, the sector is also highly exposed to increasing stress: the observed and expected climate change - with both delayed wet seasons and more intense rainfall [3] -, the growth in the frequency and intensity of hydrological extremes [4], and the steeply growing regional population [5] and

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demand for food [6], are serious reasons for concern for adaptation-constrained agricultural systems.

Currently, about 80% of the agricultural production of sub-Saharan Africa (SSA) comes from smallholder farmers [7] (representing about 60% of the regional population [8]), against a global figure of 29% [9]. Extensive rain-fed agriculture (>90% of cropland [10], compared to e.g. about 60% in India [11]) under the unpredictable and erratic rainfall patterns exacerbated by climate change [12,13] has been the leading cause of the low agricultural productivity and food insecurity [14], together with a low degree of mechanisation [15]. For instance, it is estimated that only 10% of farm power in rural SSA is mechanized [16]. In addition, estimates suggest that 10-20% of grains are systematically lost after harvest because of the lack of storage, processing and cooling equipment [17]. Lack of access to transport means and a scarce road infrastructure are further critical barriers to the marketability of local crops production [18,19]. Finally, over 90% of forest loss in Africa is attributed to "shifting agriculture" or "slash and burn" practices, which are significantly driven by low agricultural productivity - requiring more land and fertilisation by forest burning [20].

In this fragile context, most households (75% of rural SSA [21]) and businesses [22] lack reliable electricity access. In fact, about 470 out of 640 million rural dwellers contributing to the global electricity access

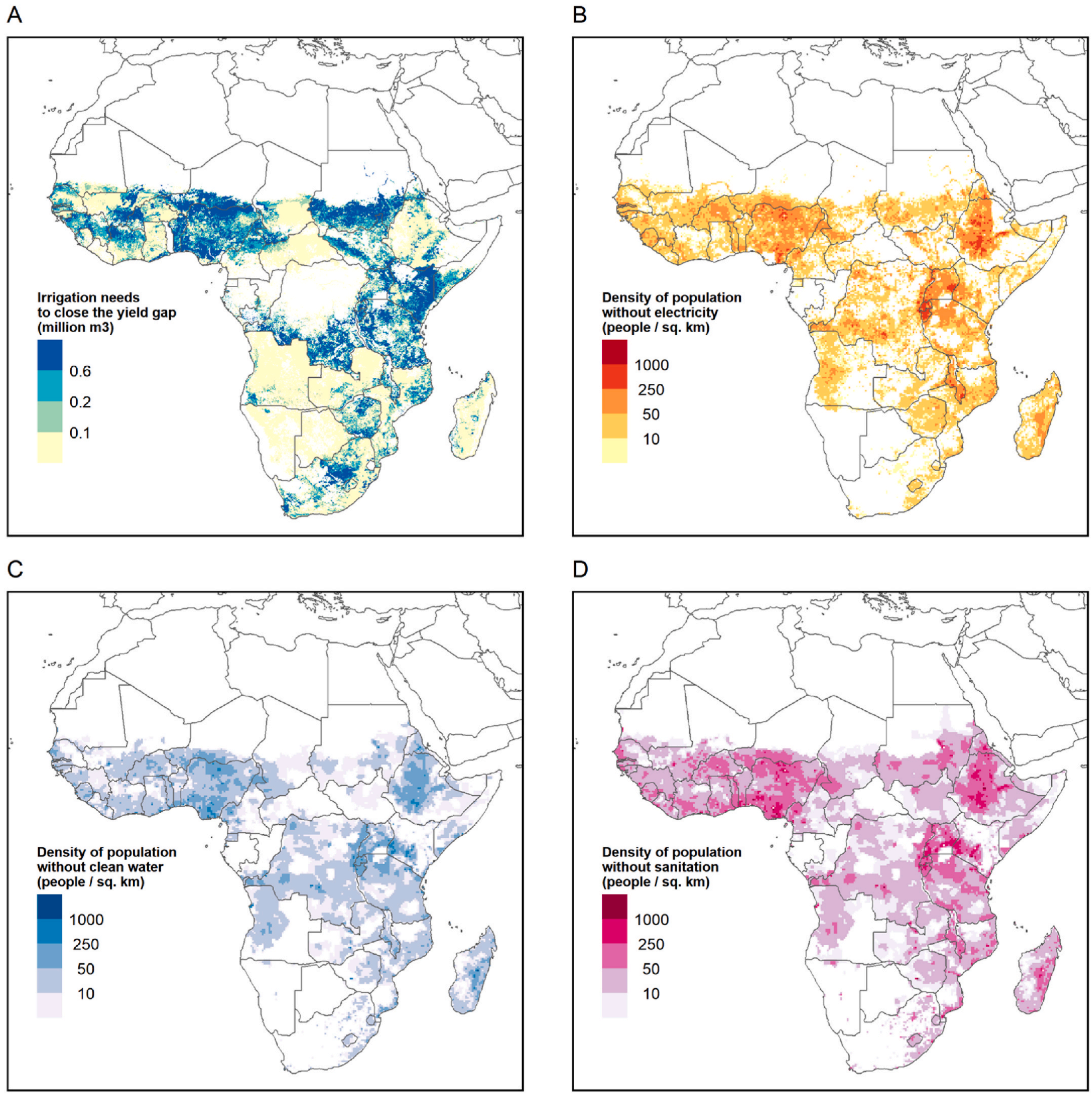

Fig. 1. Spatial distribution of critical energy-water-agriculture-indicators in SSA. (A) Irrigation water needs to close the irrigation gap in rainfed cropland; (B) Rural populations without electricity; (C,D) rural populations without access to clean water and to sanitation; Data sources: irrigation [30]; electricity access [31]; water access [32].

gap are concentrated in SSA [21]. Not by chance, the share of agricultural output processed through electrified value chains is estimated to account for only about one tenth of the total [23]. Lack of electricity also affects the capacity to pump water for irrigation purposes: in the few irrigated areas, small and medium-scale diesel-powered water pumps are prevalent and - because of the recurrent need for fuel - their operation largely relies on both farmers' finances and public subsidies [24, 25], burdening national energy utilities with debt [26], and continuing a reliance on fossil fuels and local pollution. This adds to the very low levels of access to clean drinking water and basic sanitation services (respectively 60% and 30%), which show strong linkages to energy access [27], and in some cases also trade-offs with irrigation plans [28].

Previous research has analysed technological and resource management approaches to tackle different dimensions of such development gaps. It is now key to increase the degree of integration of the different analytical tools to fully link the energy access challenge with the Nexus paradigm, and eventually reinforce the link between model-based outputs and business and investment dynamics. This is crucial to allow financing and implementing such technological transformations in resource-constrained settings. In this context, this paper intends to lay out a research agenda targeted at supporting the analysis and operationalisation of such transformations. The proposed research efforts include: (i) linking of Nexus assessment tools with electricity planning tools, with a strong focus on renewable energy; (ii) developing an accessible entry point to the modelling results able to provide Nexus insights to private and public stakeholders operating in rural areas of countries of SSA, including in the energy access, water, land and food domains; (iii) carrying out business model research to provide policy-relevant insights to facilitate private investment and public-private partnerships; and (iv) designing a flexible framework to ensure that the research agenda is replicable and scalable to other contexts.

2. Background

Lack of water and energy infrastructure in rural SSA have been reinforcing a persistent poverty trap triggering cyclical famines and jeopardising local development opportunities [29]. In particular, large parts of rural SSA show overlapping deficits in key energy, water and agriculture productivity indicators, as shown in Fig. 1A and B. In addition, the economic energy and water scarcity issues are also found in the human use domain, with large shares of rural SSA populations without clean water or sanitation services (Fig. 1C and D).

The inadequate access to energy is a key contributing factor to poverty, as energy services are crucial at different stages of an efficient agricultural value chain. The provision of electricity would enhance agricultural yield stability, productivity growth, and value addition. This situation is even more striking when considering that electricity access is widely lacking in areas that also show unmet irrigation

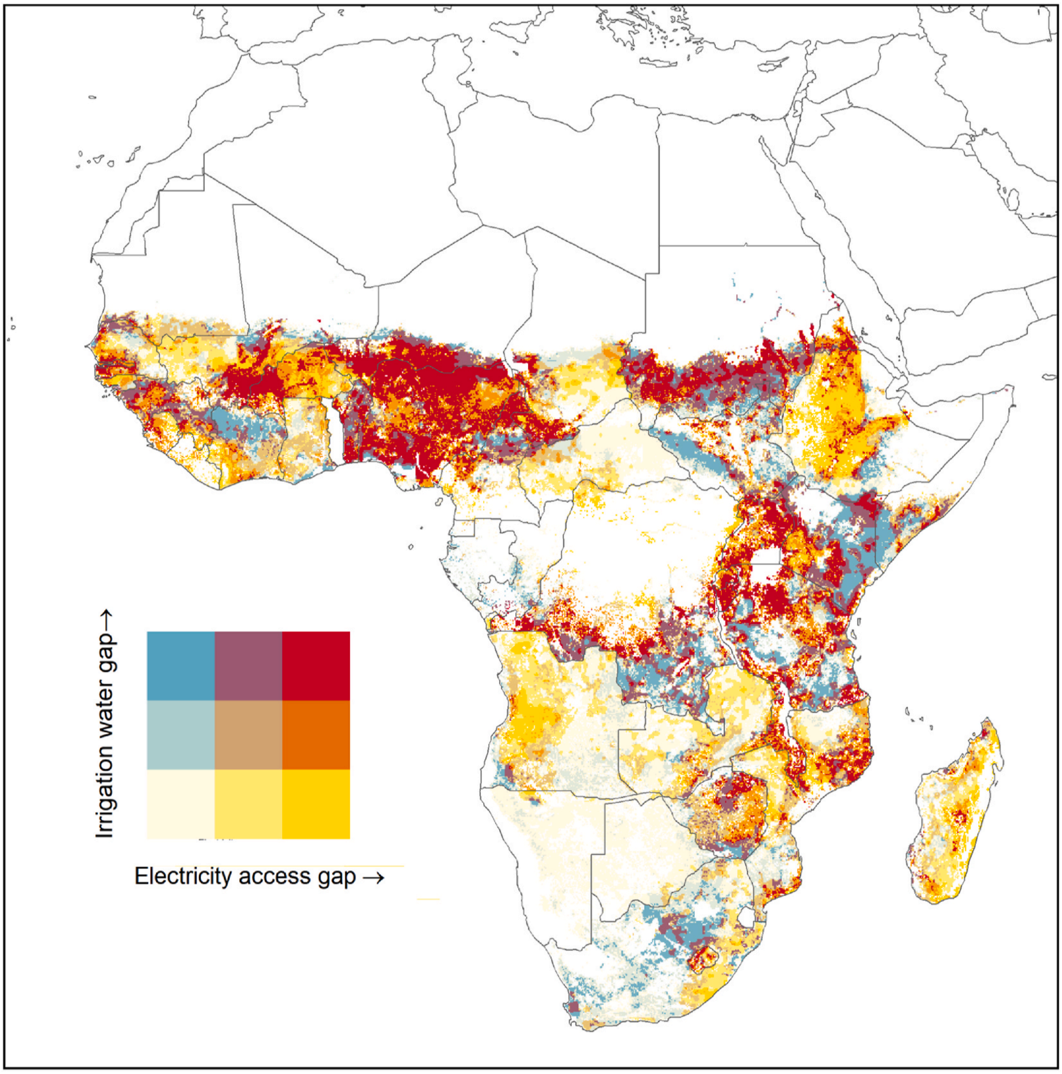

Fig. 2. Bivariate map of irrigation and electricity access gaps. Data source: authors' elaboration on data sources of Fig. 1.

demand, illustrated on a bivariate map in Fig. 2.

In Fig. 2, areas coloured in red correspond to locations where the density of the irrigation water gap and of the electricity access gap are both high, and thus where synergetic energy-water infrastructure investments could have substantial impact in reducing the two gaps. Conversely, areas in turquoise and in yellow describe areas where only one of the two gaps is predominant, and thus where a synergetic irrigation-electricity supply approach is potentially more challenging. These instances do not exclude the chance to exploit different agriculture-energy interactions: for instance, rural areas where irrigation needs are mostly met (e.g. due to favourable local climate conditions) can still greatly benefit from the input of electricity to enable local crop processing and storage. In another perspective, areas where the density of the electricity access deficit is low but the unmet irrigation water demand is high could simply correspond to either low-densely populated areas - where small scale electricity supply solutions such as standalone solar modules are preferable - or areas where there is scarce availability of water sources for irrigation, and thus where alternative agricultural transformation strategies could be considered (e.g. crop shifting or improved rainwater management strategies).

In this context, it is clear why achieving a widespread and synergetic water-energy access by 2030 is a key priority to achieve the UN defined Sustainable Development Goals for the nearly 500 million dwellers of rural SSA, expected to become more than 900 million by 2050 [5], as well as to allow for autonomous adaptation actions [33] and altogether develop a more resilient society and economy. An energy-poor and lowly-mechanized agricultural sector is a major barrier to rural development – clean energy access and mechanized agriculture would positively contribute to a number of sustainable development objectives, such as reduced poverty (SDG1), improved nutrition and food security (SDG2) and health outcomes (SDG3), equitable and inclusive education (SDG4), improved livelihoods and local economies (SDG8), as well as climate change mitigation and adaptation capacity (SDG13) [34–36]. Altogether, these transformations would also contribute to the reduction of rural-urban and gender inequalities (SDG 10) [35,37] and mitigation of potential conflict driven by food and water security concerns (SDG16) [38]. Gender-related issues are of particular importance, given the stark inequalities in employment and wage, activities, education, and asset ownership between men and women in rural SSA [39,40] as well as a lack of access to clean cooking.

To address these challenges there is a need for agricultural transformation to foster development prospects of the farmers of the continent and their communities [41–43]. The input of electricity provides a foundational building block upon which rural development becomes possible [44–46]. Reliable and sustainable electricity access enables pumping groundwater or stored rainwater, which when used for irrigation has significant potential for contributing to closing the yield gap [47–49]. For instance, Banerjee et al. [23] estimate that by 2030 power demand from agriculture for both 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. Water supply is also paramount in both aquatic and terrestrial livestock farming [50]. In addition, the electricity input enables powering agri-processing machinery (e.g. drying, milling, pressing, etc.) and storage facilities, which together could significantly contribute to increasing the profitability of harvests [51,52]. Finally, improving cross-cutting agricultural efficiencies could also provide significant co-benefits of reducing deforestation in SSA [20].

Yet, bringing electricity to sparsely-populated poor rural areas has so far proved challenging [53–55]. The key barrier to household electrification programs is that private investors generally perceive rural electrification as a scarcely profitable and risky business [56]. While public interventions to expand the national grid into remote communities with low population density and energy demand are constrained by limited state expenditure capacity, private players still largely struggle to find the economic incentive to develop decentralized electricity generation and distribution investments at a large scale. Electrification programs (and energy access development indicators) have mostly been prioritising the residential sector, an approach which has struggled to prove financially sustainable. It is increasingly evident that productive uses of energy (i.e. the use of energy for income-generating activities) and so-called “anchor customers” are the key determinants of the financial viability (i.e. of creating a commercial investment case) of electricity access expansion projects, as these customers have better ability and willingness to pay [57] and revenue generation potential.

Against this backdrop, we argue that the adoption of a Nexus approach in the design of energy access policies and business models and in the related modelling work is crucial for achieving the energy-related objectives pursued by SDG 7 in the developing world context, and chiefly in SSA. As lack of electricity access has a predominantly rural dimension, together with extreme poverty and food and water insecurity, it is clear how such dimensions are tightly interlinked. Business models to finance energy infrastructure provision should thus be centred around the Nexus dimension of the agricultural sector [58]. Hence, the question of how to electrify smallholder agricultural activities (cultivation, processing, storage and marketing) takes centre stage in the universal electrification debate. The discourse should be centred on energy use and services, rather than on energy supply, *per se* [59].

With regards to these interlinkages, the key questions which in our view have so far been scarcely addressed or which have lacked the required multidisciplinary approach to answer them entirely include the following:

- How to plan universal electricity access in rural areas, such that the Nexus dimension is fully embedded into electrification plans?
- What are the synergies between universal electrification and other Nexus objectives (water provision, food security, rural development)?
- What is its potential to unleash local economic development through the agricultural sector electrification and mechanisation, also with reference to gender equality and women empowerment?
- To address the above questions, what is the benefit of integrating local-scale, bottom-up assessment tools with large scale integrated assessment models encapsulating the Nexus dimension?
- In turn, how can a Nexus consideration of electrification investment be integrated into business models to finance electricity supply and productive appliances and applications (e.g., irrigation, milling)?
- How should public and private stakeholders co-design strategies to foster sustainable infrastructure investment in rural SSA?

The remainder of the paper defines how the H2020 project LEAP-RE RE4AFAGRI (“*Renewable Energy for African Agriculture: Integrating Modelling Excellence and Robust Business Models*”) intends to address these crucial questions.

3. Integrating rural access to energy services into the Nexus framework

Few large-scale frameworks representing the Nexus have paid explicit attention to the question of local access to electricity, including the specific link between water needs, electricity demand, climate change, the local system configuration and investment costs, and the consequences for financing energy and water supply technologies [60]. These analyses show that rural development and climate resilience are not possible without a transformation of the agricultural production system, which in turn relies on the provision of sustainable energy [61,62]. However, many of these intersections remain scarcely explored, modelled, and translated into technological, economic, and business model implications.

Moreover, whilst previous literature has investigated some of the interlinkages between agriculture, energy access, water supply, climate change, and socio-economic development, these studies have mostly been characterised by a descriptive approach, with few Nexus infrastructure and investment planning-oriented analysis. Broadly, past literature can be divided into three main strands: (i) position papers highlighting the importance of energy for agricultural development and recommending actions to be taken at different levels; (ii) energy requirements assessments in the context of agricultural development and energy access planning; and (iii) research assessing specific technologies or value chain along the climate-water-energy-agriculture-development Nexus.

With regards to the first strand, Dubois et al. [63] examine the intersection between energy access, food, and agriculture. They investigate the role of the energy input in the agricultural supply chain, while also highlighting that the agricultural sector can be a source of energy, e. g., through gasification of residuals. Relatively to business models for financing energy access, the authors discuss the concept of using the agri-food chain to support the anchor model, further discussed in Falchetta [58]. Shirley [64] 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 [64] develops recommendations to support smallholder access to value-addition supply chains in Africa through a suite of reforms engaging smallholder farmer cooperatives to ensure increased bargaining power, encourage a rapid and targeted deployment of mini-grids in village communities involved in staple and cash crop farming, and foster the creation of incentives for increasing access to micro- and commercial finance for farmers and cooperatives.

Related to the second strand, Best [65] investigates energy needs in smallholder agriculture, identifying two main types of direct energy requirements for raising productivity: (i) energy for transport to carry goods to market and supply other key services that farmers need and (ii) energy for production, processing, and commercialization of products. In the second category, the author argues that the most pressing needs come from land preparation, irrigation, crop processing, and storage. The paper highlights how value chain analysis can help pinpoint energy needs and opportunities, while also attributing considerable importance to gender-related issues. Shirley et al. [66] use geospatial analysis to identify priority areas for serving on- and near-farm electricity demand, using maize and coffee farming in Uganda as a case study. The authors identify significant areas of underserved staple and cash crop farmlands that can be served through grid and mini-grid electricity access within the next ten years. In addition, Nilsson et al. [67] develop a GIS-based approach to estimate electricity requirements for small-scale groundwater irrigation and apply it to the case study of Uganda.

With regards to the third strand, Guta et al. [68] assess the challenges and opportunities from the use of decentralized energy supply systems from a Nexus perspective based on different real-world case studies. The findings indicate that access to modern decentralized energy solutions has not resulted in complete energy transitions due to various trade-offs with the other domains of the Nexus. On the other hand, the case studies point at the potential for improvements in food security, incomes, health, the empowerment of women, and resource conservation with synergies between decentralized energy solutions and other components of the Nexus. Best [65] also reviews empirical evidence on the impacts of energy inputs in smallholder agriculture and processing based on nine case studies in the rural Global South. These case studies regard different energy consuming infrastructure installations (e.g. dryers, cooking units, mills, storage facilities, treadle pumps and irrigation systems) and analyze their impact on an array of development indicators (e.g. crop yield, farmer income, post-harvest losses, food security, production costs, crop sale price, time saved by women). In all cases, a robust improvement of the development indicators inquired is reported. Parkinson and Hunt [69] investigate the economic potential for rainfed agrivoltaics in groundwater-stressed regions, namely the potential to co-locate crops with solar photovoltaics to enable irrigation in currently rainfed only cropland, highlighting significant synergetic potential and co-benefits across land, energy, and water systems.

In addition, Gupta [70] investigates the causal impact of solar water pumps on the consumption of water and energy in Rajasthan, India. This study shows that food security, cropping intensity and extension, and income security all benefit from the adoption of solar pumps, although with the side-effect of increasing resource consumption. Omoju et al. [71] examine the impact of electricity access on agricultural productivity from a cross-country and macro perspective. Using panel data on 45 SSA countries (1980–2017), they find that promoting rural household electrification might not be sufficient for enhancing agricultural productivity. They argue that rather, policymakers should focus on electricity infrastructure intervention that supports the entire agricultural value chain.

As seen, most of the literature on rural water, electricity access and synergies with agriculture are empirical and data-driven studies reviewing historical developments and current situation [72–74]. There is a paucity of studies elaborating integrated models to plan and estimate impacts of possible future investments while elaborating on how to actually implement solutions given local financing and regulatory conditions. Current Nexus models mostly focus on centralized energy systems and their relations with water systems (e.g. hydropower, power plant cooling) [75,76], which are not suitable for assessing the requirements for rural and decentralized systems. In addition, Nexus models that explore access to energy and water in rural areas require high spatial resolution given the high sparsity and heterogeneity of settings affected by these issues [77].

In this context, Fig. 3 presents a schematic framework of the proposed paradigm, which mutually integrates energy access and the Nexus dimension. Starting from an overarching Nexus development goal, the framework ("Objectives" row) seeks to integrate energy access explicitly into existing Nexus analytical instruments ("Research" column) in order to inform decision-making and promote cross-sectoral investment ("Impact" column). To achieve these aims, the framework proposes ("Methods" row) to operate a multi-scale (from local-level to basin and country-level) and multi-sectoral (encompassing water and energy demand assessment and water, energy, climate change, and land infrastructure supply planning) model integration exercise. In parallel and coordination with the above methods, it is further proposed to design and promote business models to achieve such desirable transformations. Concerning the actors involved ("Actors" row), the framework spans from the research consortium itself and the local stakeholders (e.g., Ministries, rural development agencies, crop value chain businesses, energy access system developers), up to global institutions (e.g., development banks and global research organisations). The interaction with stakeholders is crucial to the definition of the technological space to be considered, as well as the scope of the modelling work to ensure the relevance of the questions addressed and the underlying analytical assumptions. The desired result ("Outcomes" row) of the proposed research agenda is to supply policymakers, private companies, research institutions and individuals with data-driven insights to assess technological requirements and prioritise investment flows, as well as with suitable business models that are centred around both the technical and the social aspects relevant to the contexts inquired.

4. Designing a multi-scale, multi-sectoral modelling platform

The creation of an interconnected modelling platform leveraging existing water needs, electricity demand estimation and supply planning, and Nexus assessment tools is a cornerstone of the research agenda laid out here. Fig. 4 schematically represents the proposed modelling interconnections, which – in order to capture the climate-water-energy-agriculture-development dimensions discussed above – should include:

- An evapotranspiration model to estimate the crop water demand by source (rainfall plus irrigation) as a function of the soil moisture available in the soil; assessment of potential irrigation expansion (by

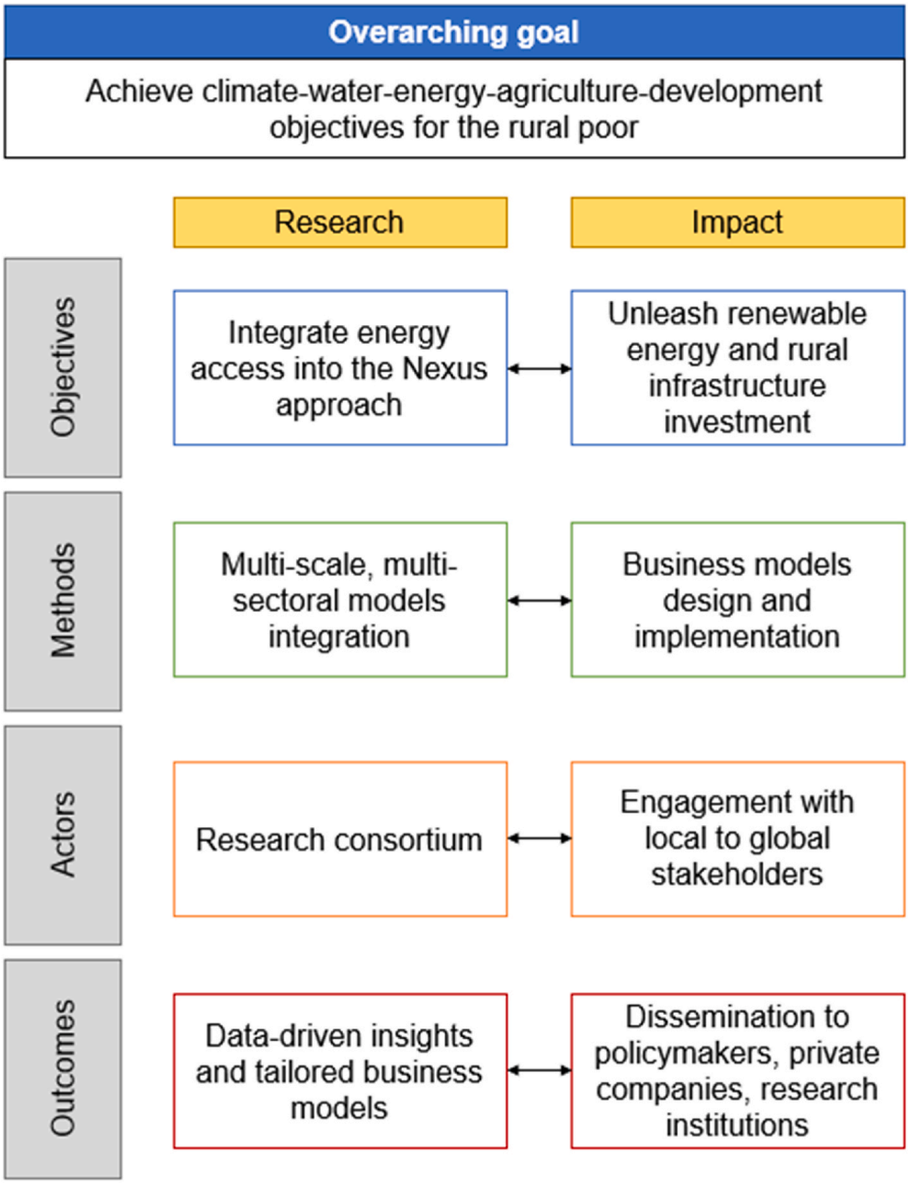

Fig. 3. Proposed framework for the energy access - Nexus research interlinkage proposed in this paper.

source, surface water or groundwater bodies) based on current yield gap). Examples of existing tools serving this purpose include WaterCROP [30], WATNEEDS [78], or the broad array of crop evapotranspiration models reviewed in Ref. [79].

- An electricity demand assessment platform covering different sectors and targeting communities where currently electricity supply infrastructure is lacking. Examples of existing tools serving this purpose include M-LED [60], research by Fabini et al. [80], Kotikot et al. [81], and Lee et al. [82], the commercial software GEOSIM Demand Analyst, or sector-specific tools such as water pumping electricity needs assessment tools [67].
- A supply-side electricity access analysis tool to assess least-cost electrification technologies and investment requirements based on electricity demand from different sectors and energy potentials). Examples of existing tools serving this purpose include OnSSET [83, 84], EC-JRC PVGIS [85], the IMAGE TIMER access model [86], or the REM model [87].
- A framework for optimizing long-term, multi-scale energy–water–-land system transformations and achieving sustainable development objectives. Examples of existing tools serving this purpose include NEST [88], the IMAGE global framework [89], Metis [90], GCAM [91], the CLEWS framework [61], the LEAP-WEAP models integration [92], all comprehensively reviewed in Refs. [93,94].

As seen in Fig. 4, the proposed platform is needs-based: it creates explicit interconnections between water needs from the agricultural sector and it links them to the related and other additional energy requirements (water pumping, crop processing, other sectors). In a second stage, supply-side modelling tools are used to assess the technological and economic requirements to achieve rural development targets, inclusive of sustainable water use for irrigation and human needs (treatment and sanitation); universal electrification and renewable energy use; and food security. In addition, the proposed platform follows the scenario logics for the assessment of changing climate conditions and different socio-economic features whilst ensuring the achievement of given policy objectives and the respect of a set of sustainability constraints.

Key characteristics of the platform should include its scalability and flexibility for different contexts based on changing the input data and tailoring the required parameters, i.e. its flexible structure, its open-

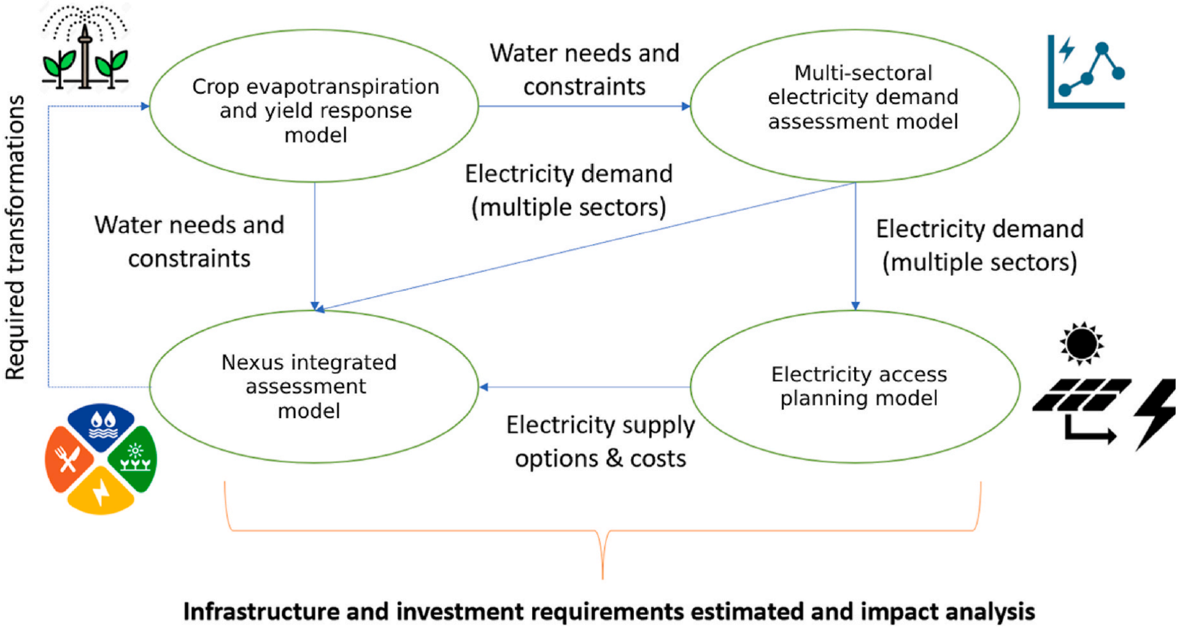

Fig. 4. Proposed modelling interconnections to develop an integrated energy access - Nexus analysis and planning tool.

source nature, and the ease of use of its outputs by an array of stakeholders through the creation of an online dashboard which can provide multi-scale, spatially-disaggregated insights based on the modelling. It is crucial that modelling insights are published in an accessible interactive dashboard, an approach useful to increase utilisation rates and impact of data-intensive analyses [95,96].

The modelling tools included in the proposed platform should also be flexible when it comes to the spatio-temporal scale of the analysis, and should aim to provide multi-level insights, from the cropland-level (irrigation needs) to the settlement-level (electricity demand and supply options), up to the watershed and national scales (integrated Nexus policies). This is a strong asset in the creation of an interconnected platform, because it would provide insights from the micro (village-level) to the macro (sub-national and national level) to the different stakeholders and for different purposes (from local system design to national policy planning).

With regards to the data considered, such a platform should leverage the most recent and high-resolution open-source, ground-truthed energy-water-land geodatabases available and process them at multiple scales to derive policy-relevant insights. For instance, satellite and statistical learning-based estimated high-resolution cropland extent [97] and estimated grid-cell level downscaled yield estimates based on official production statistics [98]. To model sustainable groundwater extraction potential and the related energy requirements, the platform should leverage groundwater availability and recharge large-scale data products [99,100] based on *in-situ* measurements. Electricity access can be proxied overlaying demographic and satellite-based information [31, 101]. Other important inputs include renewable energy potentials [102–104], historical and future climate variables [105,106], and a broad range of additional inputs, described in the bibliographic references of each modelling tool.

Such integrated platform should however not be solely based on desktop-based modelling of large-scale datasets: a cornerstone of the platform calibration and validation process lies in the consultation and engagement with local stakeholders, including the chance to conduct field visits when necessary. The crucial importance of co-design and consultation processes in Nexus research has recently been highlighted in similar settings [107,108]. Local research stakeholders can assess the reliability of the inputs considered and the plausibility of the assumptions made in the modelling, while also establishing a discussion channel with local public institutions such as statistical offices, farmers unions and water and energy utilities. These local stakeholders play a crucial role for complementing and validating the public geodatabases considered, or assisting in collecting new primary data. At the same time, they represent the core potential users of the results of the platform itself.

Finally, such modelling platform should be developed with the side objective of carrying out capacity building activity to transfer code, data, and competences that allow its use, adaptation, and replication, with the aim of expanding the pool of the platform developers and target users.

5. Implementing solutions: business models and policy research

An integrated assessment of energy needs related to small scale agriculture and water management as well as the most appropriate technologies to meet those needs would be incomplete and lacking an ultimate purpose without due consideration of the business models required to ensure implementation [109]. The low rate of electrification in agriculture and rural areas is no longer attributable to unproven technology: the main issue at hand is financial in nature [110,111]. Without much-needed investment, universal energy access will remain elusive. For example, in the mini-grid sector, by July 2020, only 13% of total funding committed by development finance institutions has been disbursed [112]. Large investments could only be attracted to fund agriculture-focused distributed renewable energy (DRE) projects if they are deployed in a financially sustainable way. Attracting more of these investments requires that DRE technologies are deployed with appropriate business models. This requires a demand-led focus that considers both hyper-local factors affecting demand within the farm or village, as well as broader factors beyond the borders of the village [63,113]. Rural smallholder farmers do not operate in isolation, but are instead nested in value chains that stretch far beyond the borders of their villages. Most of the value that can be captured from an agricultural product is currently not enjoyed by smallholder farmers, but by actors located at downstream nodes of value chains – typically in urban areas with better quality infrastructure [114,115].

Another important obstacle for smallholder farmers when capturing the value chain and obtaining revenues is lack of equipped storage facilities. Yield losses are particular evident and stringent in case of high-value perishable agricultural products such as vegetables, which are wasted or have to be sold by a farmer with no or very little margin to the intermediaries. Because of the mechanics of supply and demand, the yield season is not always the best time to make the product available, as the prices drop when the market becomes saturated [116].

As with irrigation and processing, one of the main causes of the lack of efficient and suitable storage systems is poor electricity or lack of electricity access. Thus, construction of cool sheds and cold storage facilities for smallholder farmers groups could also greatly contribute to solving this problem, avoiding food loss and facilitating smallholder farmers' access to the remunerative markets. This shifts more of the value capture upstream towards farmers and their communities, in turn catalysing local economic development. The implication is that if energy interventions for smallholder agriculture are to be financially sustainable and catalyse local development, they should be designed to not only meet the needs of the market in the immediate community, but also markets in downstream economic hubs.

This firstly requires an assessment of which agricultural activities can feasibly be performed at small scale on the farm or village. The upfront cost of equipment required to perform the activity must match users' ability to pay and there should be a reasonable economic payback period for the user. The value addition from consuming a unit of electricity should also exceed the cost thereof. Oilseed pressing, for example, is often suitable for rural small-scale applications because the equipment is affordable and the value addition of pressing is high, enabling sales at higher prices. The value density of the output is also increased, substantially reducing the cost of transport per unit of output. Secondly, correct site selection for the energy intervention is essential. Villages that are well connected to markets by motorable roads will likely have the ability to transform subsistence agriculture to an income-generating activity. Villages that are surrounded by extensive farmland or indeed other productive villages can further serve as agglomeration points from where larger quantities of agricultural output can be processed and distributed.

Once value chain-linked sites with agglomeration potential and high-value agricultural activities have been identified, the focus should shift to the energy intervention that will best meet demand. The choice between standalone systems, community mini-grids or commercial captive power systems depends on whether the activity to be energised is performed on the farm or village level. Standalone solar is typically the best suited supply technology in a farm setting, especially for water pumping. Mini-grids tend to be the most suited technology for small-scale agricultural processing because the market for standalone processing machines is still underdeveloped and standalone solar machines do not compete with diesel machines in terms of technical performance and economics [117]. Furthermore, given that the economics of processing machines improve as throughput increases, concentration of inputs at a specific point (in a village) makes more sense than multiple dispersed processors each operating on limited inputs.

An additional practical consideration is the notion of delivery models. DRE service providers are increasingly realising that productive uses are core to financial sustainability. Productive users perform income-generating activities, which is linked to higher energy consumption and higher ability to pay for energy. In the case of mini-grids for example, typically only 20% of the customer base typically consists of productive users. Yet, they may account for 80% of total revenue. As a result, DRE delivery models are now more than ever being designed around productive uses. Towards this end, suppliers are finding creative ways of stimulating such productive uses through, for example, microfinancing of appliances and machinery and acting as a buyer of local agricultural outputs and selling in economic hubs.

Beyond financial sustainability, the success of energy interventions can also be assured through community-centred delivery and management. Embedding mechanisms for shared risk, responsibility and value into business model or project design holds several benefits for both supplier and community:

- Local community members receive skills training and can be locally employed in some capacity to conduct paid activities on behalf of the developer;
- For the developer, on-site presence of local agents or technicians reduces the site visit travel requirements and associated operating costs;
- Local technical upskilling and increased local incomes improve livelihoods and stimulate local economic activity;
- Shared value, in which communities receive a share of profits, aligns incentives of developers with those of communities while simultaneously increasing the spending power of consumers.

Finally, high-level actors have an important role to play in facilitating the emergence of demand-led business models discussed here. Regulatory authorities have a crucial role to support the sector, for instance by tax and import duties exemptions on Nexus infrastructure, establishing clear and favourable tariff regime for service-based models, and setting up managerial committees in districts to better serve water and electricity users in agriculture. In parallel, multilateral agencies and local banks can greatly support investment by offering technical assistance to local commercial banks to better understand the sector, deploying concessional capital to crowd in commercial investment, carrying out local capacity building activities to upskill smallholder farmers in the use of irrigation and processing machinery, or enforcing authorities for transboundary resources regulation.

6. Discussion and conclusions

In this paper, we laid out a research agenda targeted at connecting research streams focusing on renewables-based electricity access - a cornerstone of SDG7 and a crucial enabler for multiple development objectives - and the Nexus between energy access, water, agriculture and broader development objectives in rural areas of developing countries. A more productive and profitable agriculture sector is key to lifting millions out of extreme poverty, to feeding a steeply growing regional population, and to ensuring resilience against a growing incidence and intensity of hydro-climatic extremes.

To achieve these objectives, a research agenda is proposed through (i) in-depth consultation with local to global stakeholders; (ii) activities of open-source model development, calibration & validation, and interconnection; and (iii) tailored business model research. Stakeholder involvement in the context of focus groups is a cornerstone of the proposed agenda, as it allows bridging perspectives from different public and private stakeholders operating in different areas which are part of the Nexus interactions explored. This allows properly designing and calibrating the integrated modelling platform so that only relevant technologies and policies are considered, and the right values are set for technical and socio-economic parameters. Moreover, such decision-making tools and expertise should be published open-access and enriched with a documentation and capacity building activities and to ensure uptake by local research institutions as well as other interested public and private stakeholders.

In parallel, consultation with local research institutions, as well as with public and private decision makers in SSA countries is also crucial also for the business model research and implementation. Given the very tangible and urgent nature of the issues in question, a research agenda addressing the energy access – Nexus interlinkages should not only aim at producing scientifically-sound outputs, but, most importantly, at operationalising them towards implementation in order to provide a tangible development contribution. Such implementation actions include the provision of accessible data analytics and business support to smallholder farmers, rural communities, private companies, and national governments. In addition, to disseminate such knowledge, it is crucial to establish a multi-stakeholder discussion platforms about adopted business models and the necessary enabling environment (policy and regulation) in order to promote the involvement of the private sector in water-energy-agriculture integrated solutions.

In this context, the main challenges to the effective development and implementation of the proposed agenda include: (i) the research challenge of combining different modelling tools with different conceptualisation methods in a meaningful way; (ii) the different spatial-temporal resolution of these tools, which calls for a harmonisation and scaling of results; (iii) the consistency of input data, which requires particular care to ensure homogeneous assumptions and reliable results; (iv) the relevance of the analysis to both public and private stakeholders, addressed through co-design, capacity building, and dissemination activities; (v) the accessibility and ease-of-use of the results of the analysis, which must be ensured to achieve interest and uptake from actors capable of financing and implementing the proposed solutions.

Future research output will be produced to discuss the developments and implications of the here outlined research agenda.

Author contributions

G.F. conceptualised the study; G.F., A.V. and M.T. analysed the data and produced the figures; M.H. supervised the manuscript and acquired the funding; all authors contributed to writing and revising the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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