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The role of agriculture for achieving renewable energy-centered sustainable development objectives in rural Africa

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Abstract

Multi-dimensional and overlapping barriers to wellbeing severely affect many areas in rural sub-Saharan Africa. In the region, more than 90% of cropland is rainfed, less than one third of households have electricity, almost 60% of the population reports food insecurity, and more than 35% of the population lives below the international poverty line. Climate change impacts on vulnerable systems with limited adaptive capacity and strong population growth are increasing the magnitude of these challenges, slowing and potentially reversing development. Thus, there is a strong need for multi-sector interventions across multiple levels, from national policies, to regional and river catchment-scale planning, to local planning and investment. To implement such actions, it is key not only to assess technological solutions and their investment needs, but also to appraise their feasibility and implementation potential (from both a policy and a financial point of view). Here, we implement a modelling platform (RE4AFAGRI platform), which soft-links bottom-up process-based water and energy demand and techno-economic infrastructure assessment models (WaterCROP, M-LED, OnSSET) into a multi-node, national Nexus-extended Integrated Assessment Model (MESSAGEix-Nexus) for supply and investment assessment. The results of our analysis shed light on the role of water and energy demand in the agricultural sector for jointly affecting infrastructure and investment requirements for achieving rural sustainable development objectives. We find that scenarios with increased ambition in expanding irrigation and agricultural productivity result in improved diffusion and economic feasibility of infrastructure to provide universal energy access while supporting productive uses of energy. Moreover, we conduct business model analysis to appraise the framework conditions and micro and macro determinants that can ensure feasibility of investment and uptake of small-scale infrastructure, crucial for rural development. Altogether, our research demonstrates how integrated modelling with an explicit focus on Nexus interlinkages can represent the enabling role and the business conditions for renewable energy input in agriculture to become a leverage of rural sustainable development. In turn, important policy and investment-relevant insights can be derived.

Keywords: rural development; water-energy-food-development nexus; business models; integrated development policy; productive uses of energy

1. Introduction

Multi-dimensional and overlapping Nexus challenges affect many areas of rural sub-Saharan Africa [1]. More than 90% of cropland is rainfed [2], less than one third of households have electricity at home [3], almost 60% of the population reports moderate or severe food insecurity [4], and more than 35% of people live below the international poverty line [5]. Climate change impacts on vulnerable systems with limited adaptive capacity and strong population growth are increasing the magnitude of the challenge [6]. As a result, there is a strong need for multi-level, multi-sector interventions (from national policies to regional and river catchment-scale planning, to local implementation and investment) that can support the achievement of sustainable development goals. For example, rural electrification can be achieved with standalone photovoltaics, island mini-grids or main grid connections, and this in turn enables a range of different services that can improve rural livelihoods, such as water pumping and irrigation, and crop processing and storage. To implement such infrastructure, it is key not only to assess technological solutions and their cost needs, but also to appraise their feasibility and context-specific [7] implementation potential (from both a policy and a financial point of view).

In this paper, we introduce and implement an integrated modelling framework (the RE4AFAGRI platform) aiming at assessing and planning investments along Water-Agriculture-Food-Energy interlinkages through environmental (process-based) and techno-economic (energy and water supply) models with the aim of assessing the role of agriculture for achieving renewable energy-centered sustainable development objectives, as well as the financial feasibility of implementation for such solutions. The analysis is strongly focused on the role of an explicit consideration of (productive) energy demand and access expansion in shaping the Nexus in terms of resources needs, infrastructure requirements, investment, and sustainable development objectives. Specifically, we soft-link bottom-up water and energy demand and local infrastructure assessment tools into a multi-node, national Nexus-extended Integrated Assessment Model for supply and investment assessment. Ultimately, by discussing the results of technical models in relation to those of the business models analysis, we explore the key micro and macro determinants to ensure feasibility of investment, implementation, and uptake of small-scale infrastructure operating along the WEFE (Water-Energy-Food-Environment) nexus dimensions, crucial for rural development and adaptation to changing climate conditions. This replicable, scalable, open-source framework is applied to the country-study of Zambia to demonstrate how climate impacts and water and energy needs have cascading effects that shape infrastructure and investment pathways.

2. Background and literature review

Several modeling studies have been focusing on major African river basins, mostly studying the relation between agriculture activity and water management, or centralized electricity generation (e.g. hydropower) and the related water-land trade-offs [8,9]. Yet, few Nexus modelling frameworks have paid explicit attention to the question of local access to electricity for agricultural rural development, 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 [1]. The existing 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 [10,11]. However, many of these intersections remain scarcely explored, modelled with siloed approaches, and rarely 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 characterized by a descriptive approach, with few infrastructure and investment planning-oriented analysis focusing on the WEFE (Water-Energy-Food-Environment) nexus.

Broadly, the relevant past literature can be divided into four main strands: (i) position papers highlighting from a theoretical standpoint the importance of energy for agricultural development and recommending actions to be taken at different levels (e.g. Dubois et al.[12]; Falchetta [13]; Shirley [14]). These studies highlighted the role of the energy input in the agricultural supply chain and the potential of the agri-food chain to support the anchor model of electricity provision [13,15], whereby energy infrastructure expansion is made possible by the local presence of business or public facility demand sources, in contexts were the household demand only would be too low to justify investment, and hence promote rural economic development. (ii) Work focusing on quantitatively assessing and modelling the energy requirements in the context of agricultural development and energy access planning (e.g. Best [16]; Shirley et al. [17]; Nilsson et al.[18]). This work carried out systematic assessments and employed geospatial data modelling techniques to quantify energy requirements for specific agriculture-related activities (e.g. energy for production, processing, and commercialization of agricultural products) and to achieve Nexus goals. (iii) Research assessing specific technologies or value chain along the climate-water-energy-agriculture-development Nexus (e.g. Guta et al.[19]; Best [16]; Parkinson and Hunt [20]; Bieber et al. [21]; Gupta [22]; Falchetta et al. [23]; Omoju et al. [24]). This research analyzed the challenges and opportunities from the use of decentralized energy supply systems from a Nexus perspective. Solutions inquired include solar irrigation, agrivoltaics, and additional policies to improve agricultural productivity and profitability (iv) Large-scale integrated modelling frameworks, including applications on Zambia and the Zambezi river basin - the country-study presented in this paper [25,26], which tend to focus more on the macro-scale sectoral synergies and trade-off in the use and trade of energy and water resources.

Altogether, while the existing literature already demonstrated the relevance of several Nexus linkages across sectors and policy domains, current assessment models mostly focus on centralized energy systems (the central power grid) and their relations with water systems (e.g. hydropower, power plant cooling). However, these scales are not suitable for assessing the requirements for rural and decentralized systems, which are key for achieving the sustainable development goals in large parts of the Global South. 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. In this context, our paper contributes to the existing literature gap by exploring a relatively little assessed component in the Nexus modelling research, i.e. the role of agriculture in relation to the provision of energy services for achieving sustainable development objectives in rural areas. The analysis aims at explicitly elaborating around the energy access and agriculture Nexus focusing on granular provisioning systems. Moreover, it seeks at contributing to the literature integrated models to plan and estimate impacts of possible future investments while also elaborating on the challenges for the actual implementation of solutions given local financing and regulatory conditions.

3. Materials and methods

The analysis presented in this paper is based on an open-source modelling framework, which is introduced as follows. First, the four models which are part of the RE4AFAGRI platform are introduced and their integration through inputs and outputs soft-linking is discussed. Specific focus is also given to the replicability and scalability of the modelling platform. Secondly, the methodology underlying the business model analysis tool is presented. Section 4 then describes the Zambia country-study conducted in this paper and its implementation within the RE4AFAGRI modelling platform. This includes the development scenarios designed and implemented as part of this study. The following paragraphs describe each of these methodological and implementation steps more in detail.

The RE4AFAGRI models and platform

The RE4AFAGRI platform is a multi-model, open-source[1], documented[2] framework to analyse deficits, requirements, and optimal solutions for integrated land-water-agriculture-energy-development nexus interlinkages in developing countries (Figure 1A) [1]. The platform combines and soft-links four standalone, validated[3] models: (i) WaterCROP [27,28], a spatially-explicit evapotranspiration model used to estimate the crop water demand by source (rainfall plus irrigation) as a function of the daily soil moisture dynamics in the root zone and according to the potential for irrigation expansion [29] (by source, surface water or groundwater bodies) (ii) M-LED [30], a Multi-sectoral Latent Electricity Demand geospatial model to estimate electricity demand in communities that live in energy poverty. The platform leverages bottom-up data and energy modelling techniques to represent the potential electricity demand with high spatio-temporal and sectoral granularity, with specific attention to the implications for water-energy-agriculture-development interlinkages; (iii) OnSSET (the Open Source Spatial Electrification Tool) [31,32], a GIS based optimization model that has been developed to support electrification planning and decision making for the achievement of energy access goals in currently unserved locations; and (iv) MESSAGEix Nexus (an evolution of the the NExus Solutions Tool) [9,33], an integrated assessment model (IAM) that integrates multi-scale energy–water–land resource optimization with distributed hydrological modeling. Exploring scenarios of future socioeconomic and climatic change, it provides insight into how multi-sectoral policies, technological solutions and investments can deliver resilient, sustainable transformation pathways while avoiding counterproductive interactions among sectors.

The four scientific models cover a wide range of different scales of analysis (Figure 1B), allowing to capture the crucial multi-level Nexus dimensions which are at the core of the water-energy-development linkages assessed. Specifically, M-LED and OnSSET operate at the population settlement cluster level (and the surrounding agricultural land), while WaterCROP operates at the grid cell level (with a spatial resolution of 5 arc min or around 9 km x 9 km at the equator), and MESSAGEix-Nexus runs at the spatial

[1] https://www.leap-re.eu/wp-content/uploads/2023/03/LEAP-RE_D12.3-Integrated-platform-source-code-on-Github-as-main-V1-Not-approved-by-the-European-Commission-yet.pdf
[2] https://www.leap-re.eu/wp-content/uploads/2023/06/LEAP-RE-D12.4-User-guide-for-the-modelling-platform-on-Github.pdf
[3] https://www.leap-re.eu/wp-content/uploads/2024/01/LEAP-RE_D12.5-Joint_EU_AU_report_on_the_platform_testing_and_validation_activity_V1.pdf

scale derived from the intersection of administrative boundaries and hybrid hydrological-administrative units of a country.

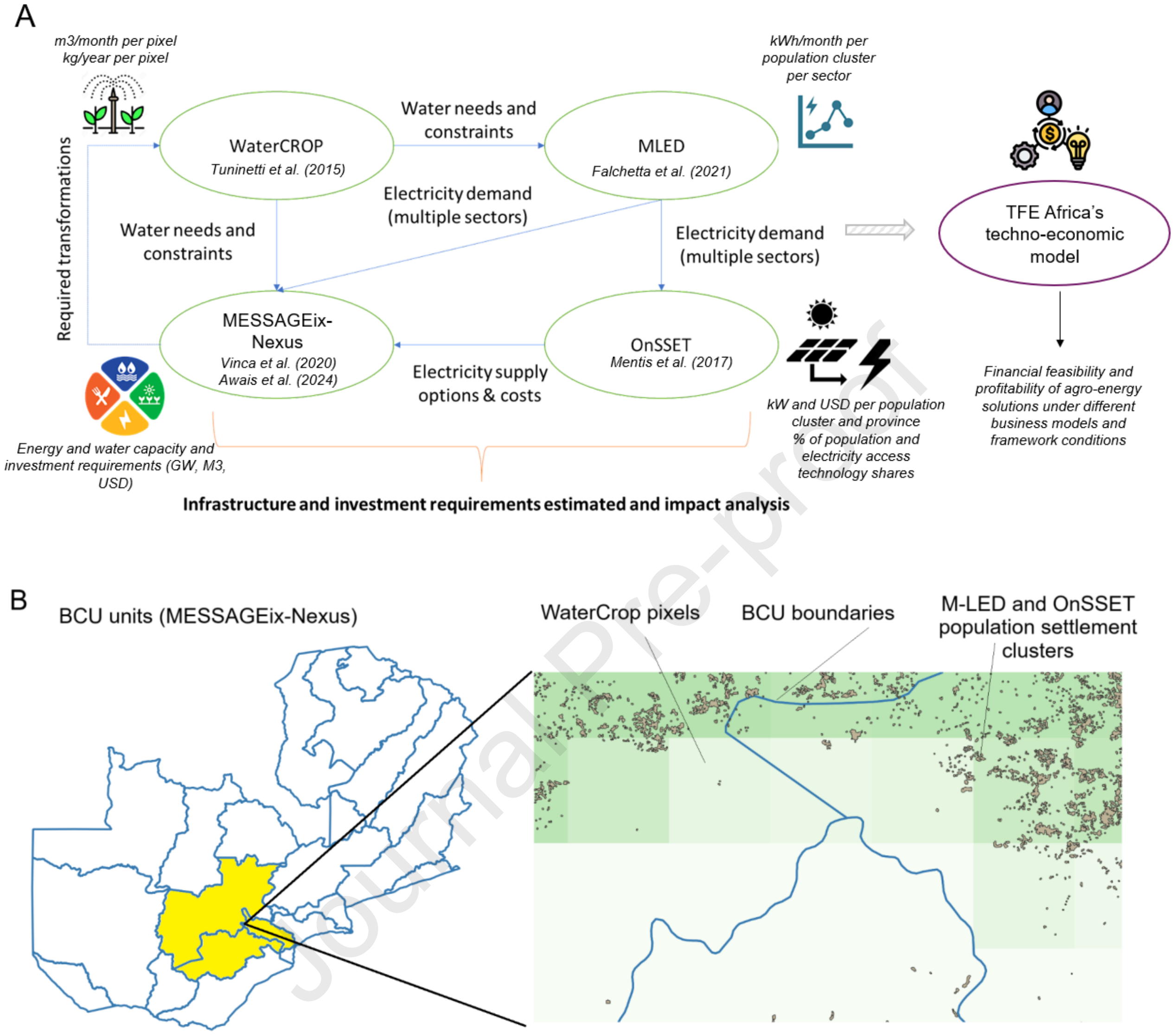

Figure 1: Workflow of the RE4AFAGRI integrated modelling platform and of the multi-scale approach, *(A) Schematic representation of the modelling platform and the model soft-linkage; adapted from Falchetta et al. (2022) (B) Schematic representation of the multi-scale nature of the RE4AFAGRI integrated modelling platform from population cluster-level [M-LED, OnSSET], to cropland pixels [WaterCrop], to hybrid hydrological-administrative units (BCU units) [MESSAGE-NEXUS] for the example of Zambia.*

The results provided by the scientific models are enriched by a techno-economic tool designed to carry out localized, context-specific assessments on the economic feasibility (from the point of view of both farmers and system developers) and the role of business models for the on-the-ground implementation of energy-water-agriculture small-scale systems, such as solar pumps, solar mills, or mini-grid powered irrigation systems managed at the community scale. It should be noted that while complementary to the RE4AFAGRI modelling platform, the techno-economic tool is not directly linked via data or model results to the platform. The main reasons are the very different scale and nature of its application: the techno-economic tool is in fact designed to perform (potential) project-specific simulations of different business models, policy and economic conditions, and cost and technology parameter to evaluate the economic feasibility and profitability of specific agro value-chain energy-powered appliances in specific contexts. It is hence a tool closer to the implementation level, while the RE4AFAGRI modelling platform operates at the location-level, and thus it is more appropriate for the policy level. Hence, the insights from the business model analysis tool should be regarded as a complementary analysis of the challenges and consideration that needs to be considered at the implementation-scale but cannot be embedded in large-scale Nexus analysis frameworks such as the RE4AFAGRI modelling platform.

Model integration within the RE4AFAGRI modelling platform

Table 1 provides an input-output data linkages matrix across the four RE4AFAGRI platform models, while a detailed report of the main input data for each of the four models is provided in Table SI1 in the Appendix. As seen from the Table, WaterCrop is at the top of the soft-linked modelling chain, meaning that it does not receive direct input from the other RE4AFAGRI models (although its climate and land inputs are harmonized with those used in the other models). On the other hand, WaterCrop provides direct input into M-LED and MESSAGEix-NEXUS (affecting water pumping electricity demand and crop processing energy demand through the agricultural throughput), and it indirectly affects OnSSET. Indeed, M-LED provides direct inputs into OnSSET and MESSAGEix-NEXUS by means of sectoral electricity demand for each settlement cluster and urban-rural stratified hybrid hydrological-administrative units (BCU units). Finally, OnSSET feeds directly into MESSAGEix-NEXUS

Table 1: Input-output model linkages matrix

	WaterCrop	*M-LED*	*OnSSET*	*MESSAGEix-NEXUS*
WaterCrop	-	-	-	-
M-LED	Irrigation water demand Potential yield increase	-	-	-
OnSSET	-	Sectoral electricity demand	-	Cost of central grid electricity
MESSAGEix-NEXUS	Irrigation water demand Potential yield	Sectoral electricity demand	Split of electricity access solutions	-

It is worth noting that in the absence of the soft-linkages detailed in Table 1 and established as part of the RE4AFAGRI platform, several Nexus interconnections would not be represented, and the local-to-national scale implications might be lost. Specifically, M-LED would not be able to provide a granular representation of the agriculture-related energy demand in the rural cluster. As demonstrated in the Results section, this share can be substantial and it can make a significant difference in determining the cost-optimal type of electricity access solution in a cluster, as well as its size and investment requirement, hence significantly affecting the national electrification strategy (see the ESMAP-GEP for reference[4]). This cascading effect is observed through OnSSET, which conventionally relies on a “flat” urban-rural tier-based approach which remains unaware of the effective productive agriculture-related activity and consequent energy needs happening in a given cluster. In turn, consideration of agricultural energy needs also significantly affects the economic feasibility, payback time and rate of return of rural electricity supply systems, as demonstrated in the analysis carried out with the TFE techno-economic tool. Furthermore, were WaterCROP, M-LED, and OnSSET not providing their irrigation water needs, energy demand, and on-grid/off-grid electricity supply shares inputs at the urban-rural stratified BCU-unit level, then MESSAGEix-NEXUS would only rely on a simple downscaling of national energy and water statistics. This would introduce a major source of error in the calibration of current resource use and in the planning of future infrastructure. The Discussion section elaborates further on the relevance of the incorporation of the Nexus soft-linkages and the dimensions which are more significantly affected.

Finally, it should be highlighted that the soft-linking and integration of the models in the RE4AFAGRI platform was tested and validated for Zambia, by involving local stakeholder discussions to help fine-tune assumptions and parameters and comparing with existing national modelling studies carried out in the country[5] (see Section 4, Implementation). An extensive technical report on the data harmonization and model interlinking can be found in Hafner et al [34].

Platform replicability and scalability

The RE4AFAGRI platform is fully compliant with open-source code and open-data principles, with the objective of allowing users to use, replicate, adapt, and scale to other geographies and scenarios the

4 https://electrifynow.energydata.info/
5 https://www.leap-re.eu/wp-content/uploads/2024/01/LEAP-RE_D12.5-Joint_EU_AU_report_on_the_platform_testing_and_validation_activity_V1.pdf

analysis presented in this paper. A Github repository (https://github.com/iiasa/RE4AFAGRI_platform) hosts the source code of the modeling platform, which, in combination with the input data bundles hosted on the RE4AFAGRI Zenodo channel (https://zenodo.org/communities/leapre_re4afagri), allows to run the analysis from scratch with customized assumptions and data, or adapt it to other geographies. Moreover, the RE4AFAGRI Wiki page (https://github.com/iiasa/RE4AFAGRI_platform/wiki) hosts the official documentation of the modelling platform, also detailing how to replicate the Zambia analysis presented in this paper and how to initialize a scaling process to another country. A set of training videos are also available in a playlist on IIASA's YouTube channel (https://www.youtube.com/playlist?list=PLEZhFf8-cpoQTM1Fol8LN8bbKJydh09Vi). Finally, the RE4AFAGRI website (https://www.re4afagri.africa/business-models) hosts the TFE techno-economic tool and its documentation.

Business models analysis: methods and assumptions

As a complement to the RE4AFAGRI modelling platform (Figure 1), a techno-economic tool was developed as part of the RE4AFAGRI project to determine the financial viability of electrifying agro-processing and irrigation activities from the perspective of the smallholder farmer[6]. The business model analysis tool calculates the payback period of a smallholder farmer's purchase of solar water pumps and agro-processing machines. In other words, it calculates the time (in months and years) it would take the farmer to recover the initial capital expense. The model also measures financial viability in terms of net present value (NPV) and internal rate of return (IRR). The model considers a very wide set of variables as inputs (Table 2): it is sensitive to the number of hours that the equipment is operational per day and throughout the year, input costs such as electricity tariffs and maintenance costs, the price margin of the crop being sold, whether the farmer rotates between crops, and more.

In parallel to the techno-economic tool, an assessment of best practice business models for standalone and mini grid electrification of smallholder agriculture was also conducted. Particular focus was placed on pay-as-you-go (PAYGO) permutations, appliance financing approaches, "KeyMaker" models and community-centered models. PAYGO and appliance financing approaches are especially useful as they address the challenge of high upfront expenses through payment plans, while the

[6] https://www.re4afagri.africa/business-models

KeyMaker model serves as a way for the energy supplier to support the farmer to sell their newly processed crops in downstream markets where better prices can be achieved.

Table 2: Key input parameters to the techno-economic tool

Parameter	Unit
Operational hours per day of the equipment	hours/day
Operational months per year of the equipment	months/year
Grid tariff (if the equipment is connected to the main grid)	USD/kWh
Mini grid tariff (if the equipment is connected to a mini grid)	USD/kWh
Current price per liter of diesel	USD/l
Distance from farm to market and back	km
Fuel consumption of the vehicle transporting crops to market	l/km
Estimated spend on equipment maintenance per year	USD/year
Monthly salary of the equipment operator	USD/month
Upfront cost of the equipment	USD
Power rating of the water pump / agro-processing machine	kW
Maximum possible throughput of the agro-processing machine	kg/hour
Price of unirrigated or unprocessed crop	USD/kg
Price of irrigated or processed crop	USD/kg

4. Modelling platform implementation

Zambia country study description and model implementation and calibration

Zambia is a landlocked country in southern Africa, representing a relevant example of growing environmental pressure due to climate change (with changing rainfall patterns, increasing water scarcity, and threats to both agricultural productivity and hydropower reliability) [35–37], and a growing population and economy [38,39], where it is crucial to assess and plan infrastructure, policies and investments along the water-energy-food-climate-agriculture nexus. Zambia boasts abundant water resources (Figure 2A; Table 3), primarily sourced from the Zambezi River and its tributaries. The availability and management of water are central to the agricultural sector, which forms the backbone of Zambia's labor source and whilst accounting for almost 60% of employment [5], it has a very limited value added (only 3% of total GDP [5]).

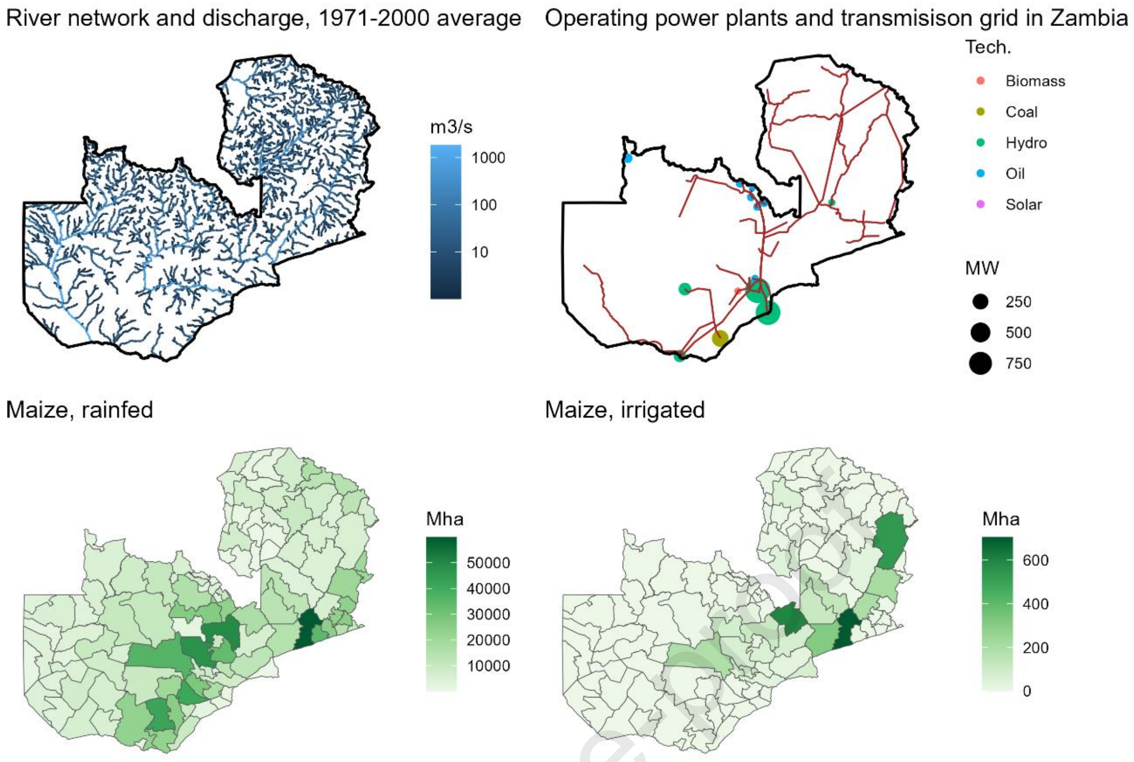

Figure 2: Maps of selected water, energy, and agriculture statistics in Zambia. *Data sources: river network* [40]*; power plants* [41]*; annual agricultural harvested area (rainfed and irrigated areas) for year 2010* [42]*.*

Table 3: Selected statistics for Zambia WEFE Nexus

Dimension	***Variable***	***Value***	***Source***
Economy	Share of GDP from agriculture	3 (% of total)	[5]
Economy	Share of employment from agriculture	60 (% of total)	[5]
Economy	People classified as "extremely poor"	48 (% of total)	[43]
Energy	Electricity demand	17.6 TWh/yr.	[44]
Energy	Share of population with access to electricity	34 (% of total)	[3]
Socio-demographics	Population	21 (million people)	[5]
Socio-demographics	Rural population share	54.3 (% of total)	[5]
Water	Hydropower production	91 (% of total)	[44]
Water	Share of irrigated cropland	4 (% of total)	[45]
Water	Share of people with access to safe water	64 (% of total)	[46]

Electricity demand in Zambia: the mining industry consumes roughly 50% of electricity in Zambia and is a non-negligible part of GDP. The mining sector is covered by the electricity demand estimates and projections carried out in this paper - thus affecting the results of the analysis. Yet, it should be noted that it remains marginal in our analysis because our paper mostly focuses on the role of rural areas and agriculture. Final energy demand (which includes non-electric commodities, Figure 3A) is dominated by the residential and commercial sector, followed by industry, public sector (non-commercial) and transport. The energy consumption in the agriculture sector is currently negligible compared to the aforementioned.

Water demand in Zambia: Hydropower is the first in terms of freshwater withdrawals in Zambia, with about 1 km^3 in 2020. However, most of the water used for electricity generation is reusable downstream. Other demand sources, which are mostly water-consumptive, are municipal, industrial and irrigation. In 2020 irrigation was still not the major source of water withdrawals (Figure 3B), with room for increase in some basins.

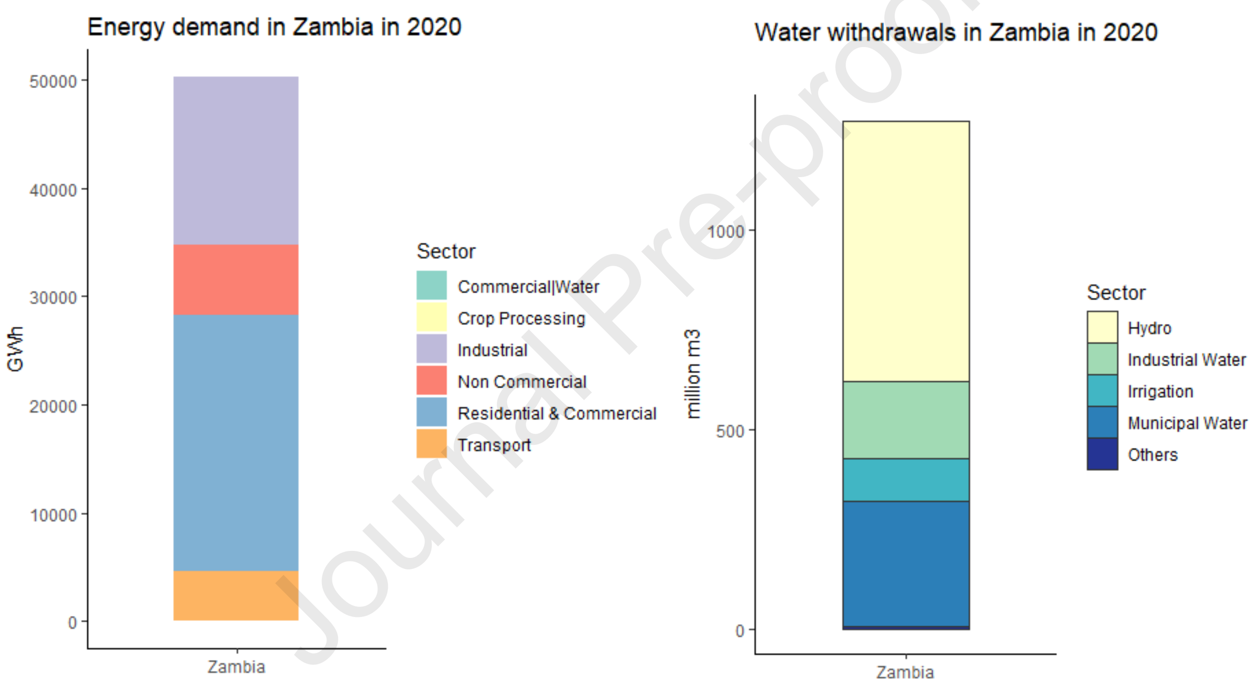

Figure 3: Final energy demand and water withdrawals sectoral splits in Zambia in 2020

Electricity generation in Zambia is intricately linked with both water and agriculture: hydropower, the dominant source of electricity generation (currently producing 91% of the national consumption, at 17.6 TWh/yr. in 2022 [44]), relies heavily on the country's water resources. Variations in water availability due to climate change can thus have a cascading effect on energy production, affecting not only the power sector but also the irrigation systems crucial for agricultural activities [47,48]. Previous research demonstrated that climate change impacts imply a reduction in capacity factors and reliability of hydroelectric power in the Zambezi river basin, as well increasing sectoral competition for water resources [36,49]. With regards to energy access, currently Zambia has a national electricity access rate of 34% and a governmental target of full electrification by 2030 [50]. The low population density in the country (28 people/km^2) contributes to the challenge of extending the national grid, especially in rural areas, where the bulk of the deficit communities are located. In addition, as discussed in Mfune and Boon [51], Zambia is currently affected by a limited uptake of renewable energy technologies in rural areas due to inadequate policy provision and implementation, lack of awareness among rural households about the benefits of renewable energy, the high capital costs of technology and the undeveloped nature of renewable energy markets.

The RE4AFAGRI models are calibrated, as documented in Hafner et al. (2023), using recent energy and water statistics (See Tables SI1A-D for an account of the input and calibration data to each model), as well as with inputs from stakeholder groups to define the value of a set of technical parameters and cost assumptions. Finally, it should be noted that differently from previous developments of the model and from other Nexus integrated models applied to the Zambezi region, the version included in this framework does not have a dynamic representation of the river flow and storage. This simplifies the model but also means that we do not consider upstream-downstream responses of water withdrawals. We justify this choice being our focus mostly on rural off-grid power generation, rather than on hydropower management and centralized electricity generation. Irrespective of this limitation, it should be noted that transnational water transfers within the same basin are considered boundary conditions.

Scenarios, development pathways, and their implementation

In the implementation presented in this paper, we developed three scenarios based both on the SSP-RCP framework [52,53] used in the Integrated Assessment Modelling community (Figure SI3) to evaluate future pathways and impacts in relation to energy and climate change, and on a scenario design process which is specific to the rural developing realities addressed by the framework implemented in this paper. The SSP-RCP logic determines the future narratives and trends in fundamental socio-economic elements (population, GPD, urbanization), as well as the impacts of climate change on land, water, and energy systems. Figure SI4 illustrates the projected socio-economic and climate change pathways in Zambia under the SSP-RCP framework.

The additional scenario dimensions are instead specific to the development policies which are most relevant for the WEFE Nexus assessed with the RE4AFAGRI project. The design of the latter component was the result of a participatory workshop and in-depth discussions with stakeholders (see SI Appendix for a Table of involved stakeholders). In this context, Table 4 illustrates the three scenarios assessed in this paper. The baseline scenario represents an extrapolation of recent trends into the future, and it serves to highlight potential challenges in absence of changes in trends (e.g., persistent gaps in energy, water access and adequate nutrition). In the improved access scenario, some efforts are made to improve the quality of living in the case-study country, by increasing energy, water, and sanitation access so that the access gap estimated in the baseline (percentage of population remaining without access) is at least halved by 2030. A food nutrition target also aims at ensuring domestic food production by improving crop yields through irrigation. Finally, the ambitious development scenario includes ambitious and ideal targets of universal access to electricity, water, and sanitation by 2030, and domestic agriculture production improving to meet decent living nutrition standards (EAT Lancet diet [54]). In addition, measures to guarantee 100% renewable electricity generation are in place. This scenario includes different levels of ambitions in improving the production and access to electricity, water infrastructure and water for agriculture, with different grades of investment requirements or secondary impacts on natural resources (e.g., coal or water withdrawals). Additional scenarios could be run up to assess the sensitivity to specific model parameters (e.g., technology costs) or to address specific questions (e.g., intensification vs extensification of agriculture, or achieving targets in 2030 and or 2050 etc.).

Table 4: Policy scenarios modelled

Scenario	**Socio-economic**	**Climate change**	**Agriculture and food targets**	**Electricity access targets**	**Additional development targets and policies**
Baseline	SSP2	RCP 7.0	project historical trend of production	Current policies	Current policies
Improved access	SSP2	RCP 7.0	increasing water supply to meet domestic food crops production demand in 2030[7]	halving the gap by 2030	water access & sanitation: halving the gap in 2030
Ambitious development	SSP2	RCP 7.0	increasing water supply to improve yields and meet future food crop production demand consistently with the EAT Lancet diet in 2030[8]; Renewable electricity share = 100% + climate constraints	universal access	universal water access & sanitation

[7] Given current diet, no extensification, fertilization, trade.
[8] https://eatforum.org/eat-lancet-commission/the-planetary-health-diet-and-you/

This scenario choice enables comparison of historically observed development trends with goals set by the Sustainable Development Goals. Different levels of ambition and speed of change can provide policy makers with an estimate of the financial requirements and combined with development. Figure 4 compares the level of ambition of the scenarios across the WEFE development objectives set.

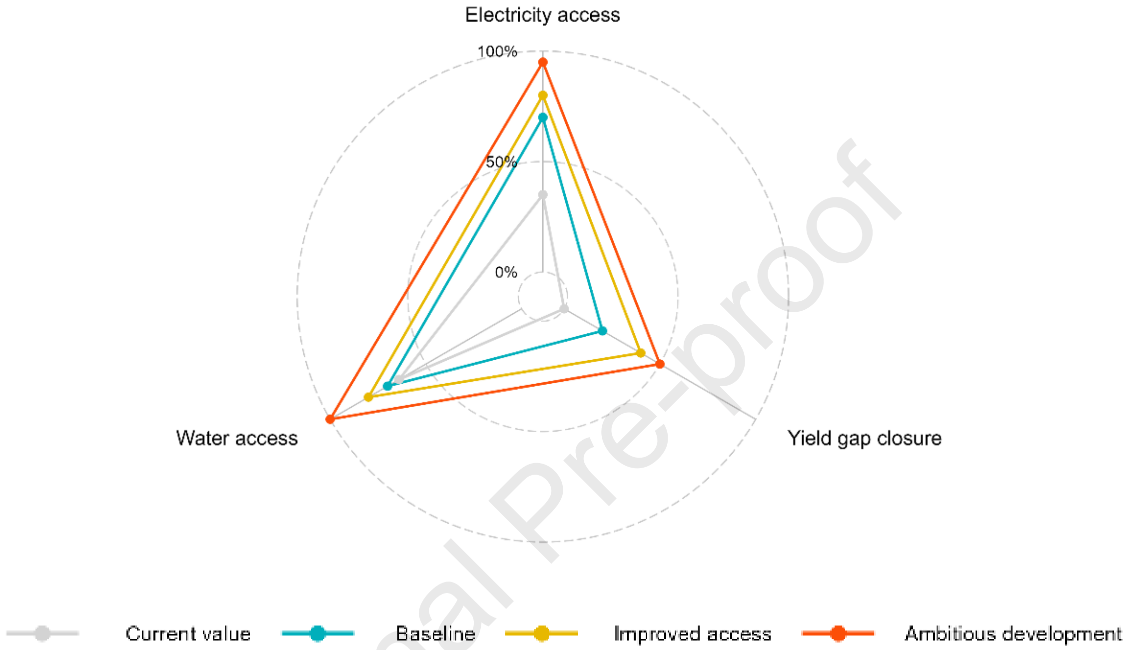

Figure 4: *Radar plot of the key development dimensions addressed by each scenario, compared to the current values (sources reported in Table 1).*

Statistical analysis of results

While most of the figures presented in the Results section are based on the direct output from the models, we conduct an *ex-post* statistical analysis on the M-LED and OnSSET results to appraise the relevance of agriculture-related demand for electricity access pathway, a key issue given our main research question. To achieve this aim, we combine cluster-level energy demand estimates from M-LED in each scenario, we calculate variables indicating the total cluster demand (across all sectors, *TOTDEM*) and the proportion of the local demand that is related to agricultural sectors (*AGRISHARE*), and we combine such statistics with cluster-level OnSSET results indicating the cost-optimal electricity access solution at each year and in each scenario (*ELYTECH*). Based on the joined model results dataset (which jointly covers all scenarios results), we estimate the following multinomial logistic regression models, which allow estimating the association of a set of predictor variables *X* with the probability of a given class *i* of the categorical outcome variable *ELYTECH* with respect to a base class *j* of the that variable. Specifically, separately for years 2030 and 2060 we estimate the following:

$$ELYTECH_{ist} = TOTDEM_{ist} + AGRISHARE_{ist} + SCEN_s + \epsilon_{ist}$$

where *i* is each rural cluster covered by the M-LED and ONSSET models, *s* is each of the three scenarios assessed in our study, and *t* is each of years 2030 and 2060 (medium and long-run model horizons). ϵ_{ist} represents the residual error term.

5. Results

Granular estimates of water and energy needs for agriculture

The WaterCrop model for Zambia projects (Figure 5, bars on the right) that in 2030, 141 [95-187, scenarios range] MCM (million cubic meters) of water will be required to achieve the irrigation expansion goals set by the three scenarios assessed, growing to 425 [239-610] MCM by 2050. Thanks to the input of irrigation water, WaterCrop estimates that yields will increase considerably. For instance, under the assumption of availability of other inputs, maize yield may reach 8.1 ton/ha (+242%) by 2040, hence getting closer to the typical yield values obtained in temperate climates. Rice may see a significant increase reaching an average yield of 6.8 ton/ha (+423%) by 2040.

In response to the projected water demand and agricultural production growth, the agriculture-related electricity demand in rural areas as a share of the total electricity demand (a measure of the intensity of productive uses of energy related to agriculture) is estimated to grow by the M-LED model from the current negligible levels to 1.3 [1-1.6]% in 2030 and to 1.9 [1-2.9]%[9] of the total demand in 2050, demonstrating the relevance of promoting policies to foster the WEFE Nexus sectors for promoting productive uses of energy. While these country-wide shares might seem marginal, Figure SI5 quantifies the distribution of such agricultural share growth across clusters, where the growing relevance of agricultural loads in rural areas with time and scenarios becomes much more evident. In many rural clusters, the share of agricultural-related demand is significantly larger. For instance, in the ambitious development scenario we estimate that by 2050 in almost one out of ten rural clusters, agricultural loads

[9] The ranges of these shares refer to the three scenarios assessed, where the irrigation water and the crop processing throughput volumes estimated in WaterCrop affect energy demand estimates in M-LED.

will account for >10% of the local electricity demand and - in almost one out of twenty - for >25% of the total demand. Moreover, it should be noted that these shares are relative to the total demand projections, which project final electricity demand in Zambia to climb from the current 17.6 TWh/yr to 71 [55-93] TWh/yr in 2030 and 98 [87-116] TWh/yr in 2050, as depicted in Figure SI6A, presenting sectoral energy demand results. It should be noted that a large share of such electricity demand growth is driven by the residential, SME, and mining sectors - which have only loose direct links with the agricultural sector. Yet, as seen from Figure SI6B, our scenarios are designed to be focusing on agricultural sector policy and their resources and infrastructure implications, with more limited differences across scenarios in the non-agricultural sectors.

The relevance of agricultural demand for electricity access pathways

Given our emphasis on representing the agriculture-related Nexus interconnections by means of model linkages, it is important to evaluate how rural development objectives in terms of irrigation, food production, and its local processing affect energy planning. Looking at electricity access expansion results, we run multinomial logistic regression analysis on the OnSSET model results to assess the change in the likelihood of a cluster being cost-optimally electrified by standalone PV (*vis-à-vis* mini-grid or central grid electrification). As demonstrated in Table SI2A, for the year 2030 (medium-run) we estimate that each percentage point increase in the share of rural electricity demand that is agriculture-related, increases by around 12%[10] the odds (after controlling for total local electricity demand in each cluster and the differences across scenarios) of cost-optimal electricity supply via standalone systems *vis-à-vis* grid-based connections. Yet, when moving to the long-run (year 2050), in Table SI2B we observe that this difference in odds is nearly nulled across electrification solutions: newly connected rural clusters (which in the previous time-steps were too expensive to achieve, due to remoteness or to low demand density) with a high intensity of agricultural activity become almost equally likely to be served through national grid extension. This finding highlights the crucial importance of supporting agricultural-centered decentralized electricity access systems to accelerate rural development in the next decades and avoiding a delayed provision of electricity through the national grid.

[10] The odds change is derived by exponentiating the coefficient estimates and subtracting 1 from the result.

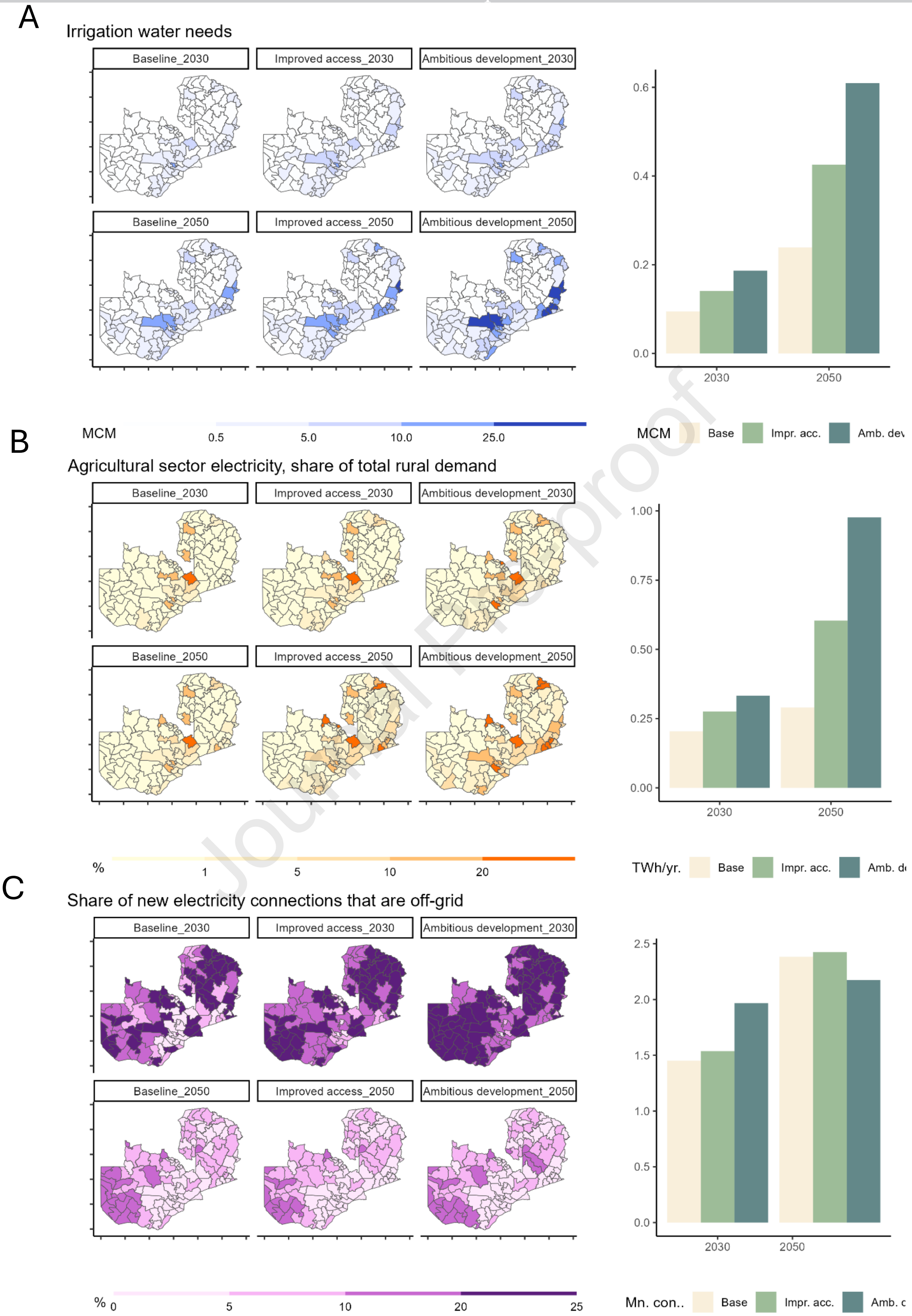

Figure 5: Water and energy: demand and access in 2030 and 2050 as derived from bottom-up assessment in the RE4AFAGRI platform, by scenario. *Left panels show the spatial distribution of each*

variable across administrative units; right panels show country-level (aggregated) values. ***(A)*** *Irrigation water needs (in top of rainfall) to achieve the yield growth targets;* ***(B)*** *Share of the estimated electricity demand in rural areas that is related to agriculture (irrigation; crop processing and storage);* ***(C)*** *Share of the estimated new electricity connections that are optimally served by off-grid solutions (mini-grid and standalone systems).*

Zooming in and looking at the sub-national level heterogeneity (Figure 5, maps on the left) clearly demonstrates the existence of a spatial overlap between irrigation water demand (at different levels of irrigation expansion ambition), and the related electric energy demand in rural areas. In turn, we observe that such water and energy needs for agriculture jointly shape energy access pathways: areas and scenarios with higher density of rural agriculture productive energy demand also have significantly higher economic feasibility of off-grid energy supply systems. This means that there is high economic potential for combined mini-grid and irrigation development in the short run, with positive impacts on both energy-consuming productive activities and residential electricity access. This requires coordination and planning between mini-grid developers, farmers and local governance. In the long-run, communities still lacking access to electricity are eventually reached by the national grid and mini-grid providers will have the chance to also connect to the national grid. Another important implication is that the switch towards mini-grid systems due to higher productive demand is relatively strong already in the “improved access” scenario compared to the baseline scenario, suggesting that even moderate agricultural productive demand stimulation can have a beneficial effect in making mini-grid systems that provide community-wide energy access more feasible and widespread.

Nexus policy planning benefits from bottom-up assessment of water and energy sectors

Once granular demand and access modelling shed light on how water and energy needs in the agricultural sector can shape infrastructure planning, it is crucial to consider the main scales at which strategic policy and investment decisions are taken: the national (and sub-national administrative) government, and the river basin and catchment scales. Using the MESSAGEix-Nexus multi-node Nexus integrated assessment model, which is receiving as input the bottom-up electricity and irrigation water demand from M-LED and WaterCrop and the local optimal electricity access and technology shares from OnSSET, we appraise the three scenarios by aggregating the bottom-up generated water and energy demand layers, as well as the cost-optimal electrification shares.

As seen from Figure 6, we find that the baseline and improved access scenarios display similar results in terms of electricity supply, while the ambitious development implies a larger leap, especially in the longer term. Looking at the technological shares, hydropower remains the dominant source of electricity in Zambia due to the large and cheap (at least, at the power unit margin) untapped potential [55,56]. In absence of further policy, coal constitutes a significant share but would be largely replaced by utility-scale solar and off-grid systems in the ambitious development scenario, which stipulates that no new coal power plants can be developed. In addition, it is relevant to observe how in all the scenarios the off-grid capacity (including both standalone and mini-grid systems) experiences a surge from 2030, which then later decreases to be replaced by the national grid moving towards 2050.

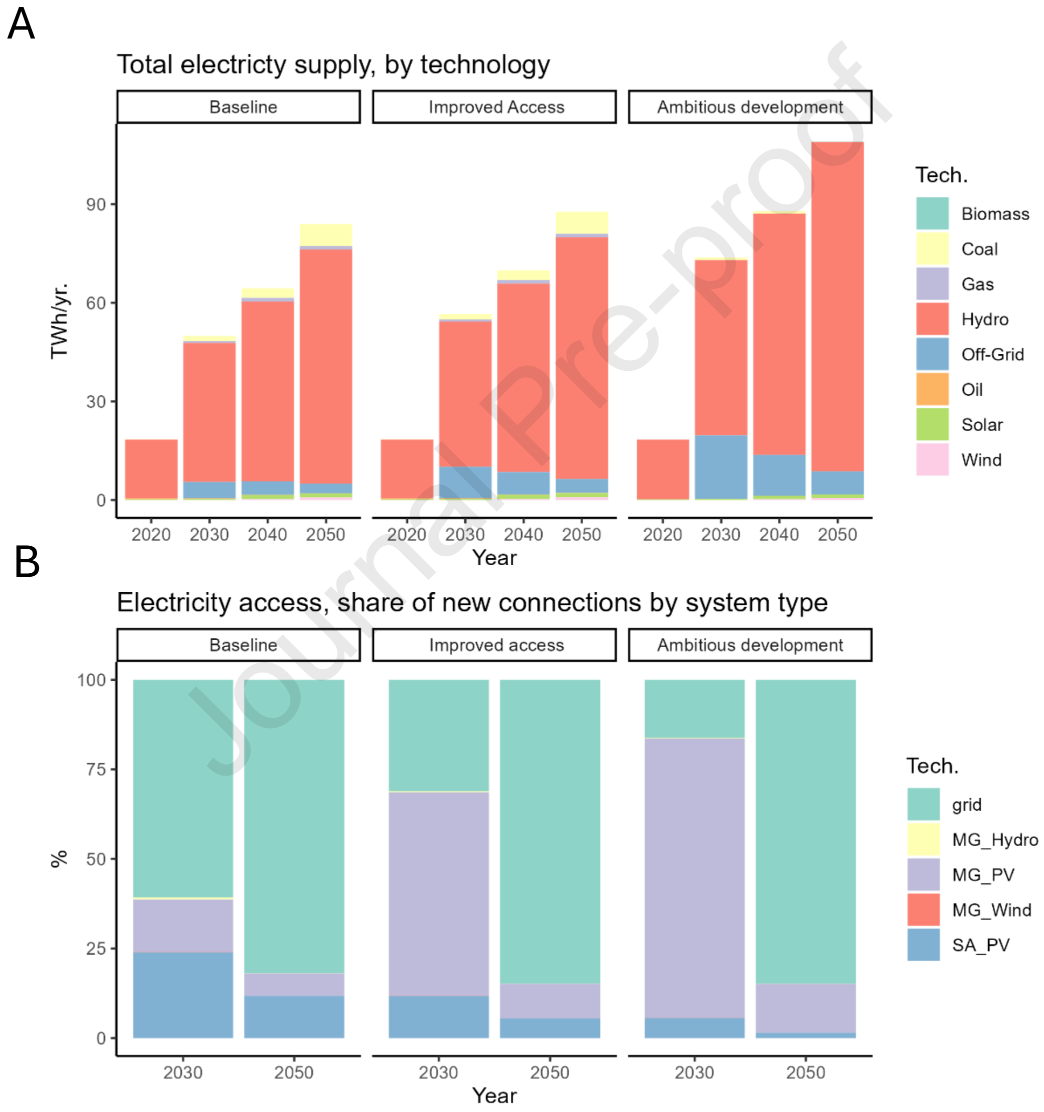

***Figure 6: Electricity supply and access expansion: optimal strategies** (A) multi-node central energy system planning and (B) bottom-up electrification modelling.*

As seen from Figure 6A, the off-grid technology is a non-negligible share of electricity supply in some scenarios, nonetheless, as seen from Figure 8A, it is a negligible share of the costs. This result is the consequence of both hydropower being significantly more expensive than off-grid systems and of the bulk of the final total electricity demand (including all sectors) being non-off-grid, as it stems from the growth of the industrial and commercial sectors. The dominant use of hydropower in the region is possible because of the large, still untapped potential and the large water availability. Hydropower is also a fundamental technology for managing water resources through the year and regions. Rapid socio-economic growth in Zambia will lead to substantial increase in water demand for municipal and industrial purposes, as projected in Figure 7 for the baseline scenario. In wet seasons, both ground and surface water resources are available, while in dryer seasons groundwater is more scarce and alternative sources such as recycling and reuse might be important especially for agriculture. In the improved access and ambitious development scenarios agricultural production is significantly increased and affects water resources. Theoretically there will be enough water to meet also very high seasonal demands, but in real-word experience this implies efficient management of water reservoirs with hydro dams and flood and drought management plans. The area has experienced severe droughts, the latest being currently experienced in Q1 2024[11] and the phenomenon being projected to increase with climate change.

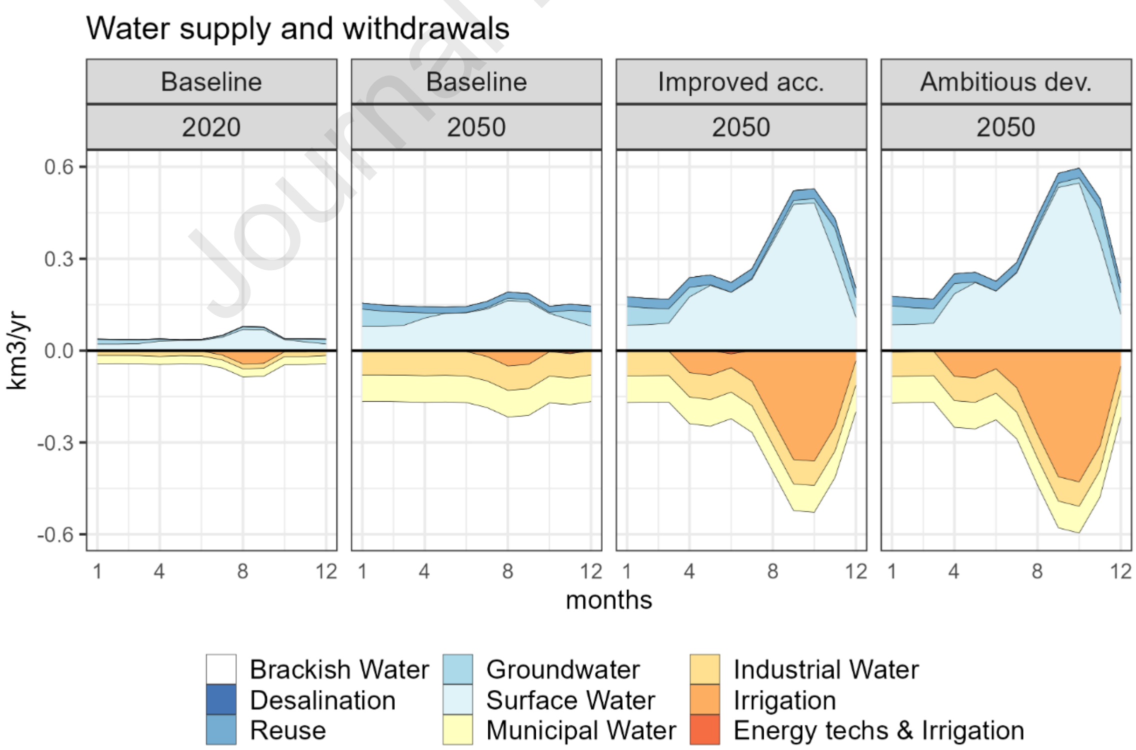

Figure 7: *Water balance of Zambia in 2020 and 2050, by scenario*

[11] https://www.aljazeera.com/news/2024/2/29/zambia-declares-national-disaster-after-drought-devastates-agriculture

Moving to investment requirements (Figure 8A and Figure SI1 for the average annual expenditure), it is expected that hydropower takes the lion's share of investments in electricity generation. While the baseline and improved access scenarios display similar ranges of values ($1-1.2 billion per year of investment in 2030), investment climbs much quicker in the ambitious development scenario, peaking with $1.6 billion in 2030, where the off-grid sector becomes the second technological sector by investments, after hydropower. The large difference in investment in hydropower and off-grid generation can be explained by looking at the technological capital costs. The ambitious scenario suggests a new installed capacity in 2030 of 700MW from hydropower at the capital cost of 1,942$/KW and about 107MW of rural off-grid generation capacity at the capital cost of 570 $/KW. Investment in the following decades fluctuates but remains in a similar range of values. Looking at operational expenditure of the electricity sector, hydro also dominates the flow, followed by costs related to the electricity transmission and distribution grid management. The across-scenario difference is more limited and shows a consistent climb from less than $300 million per year in 2020 to about $1 billion per year in 2050.

On the other hand, water infrastructure investments (Figure 8B and Figure SI2 for the average annual expenditure) show much larger differences across the scenarios, with marked differences between a baseline scenario (based on prosecution of historical trends in irrigation expansions and clean water access) and the improved access and ambitious development scenarios, which are instead more similar to each other (yearly investment in the range of $600-750 million per year in 2050). In the latter scenarios, irrigation is the leading source of investment, with distribution, pumping, treatment, and recycling having similar smaller shares. On the other hand, operational expenditure shows less dramatic differences across scenarios, with treatment and recycling being the prevalent source of investment.

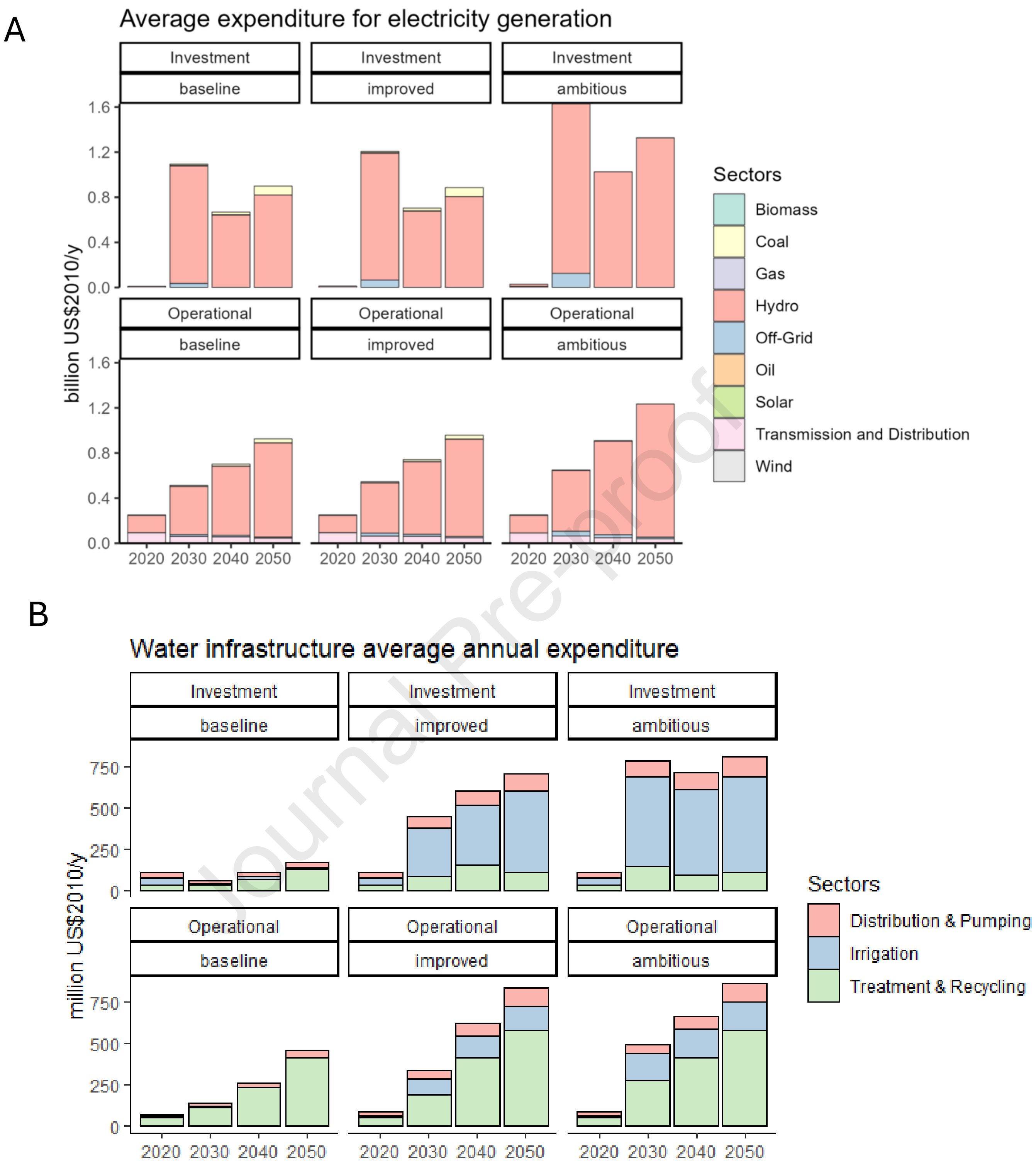

Figure 8: *Investment and operational expenditure in the (A) energy and (B) water sectors, by year, scenario, and technology*

Feasibility of small-scale infrastructure implementation: the role of business models

Once infrastructure and investment requirements are estimated, it is key to assess how a set of key conditions (policies, regulation, and business models that foster investment, and take-up of solutions [57]) is responsible for successful implementation, especially at the granular scale of decentralized energy and irrigation water access technologies. To achieve this aim, the techno-economic tool was used to simulate different scenarios to assess the impact severity of the different solar water pump and agro-processing inputs (presented in Tables 4A and 4C, respectively).

Table 4A: Inputs to illustrate scenarios of techno-economic viability of a solar water pump for maize cultivation in Zambia

Input	Unit	Base case	Scenario 1	Scenario 2
Selected irrigation scenario pertaining to seasons irrigated per year[12]	N/A	Mono-cultivation	Crop rotation	No
Upfront cost of the pump	USD	738	600	500
Irrigated maize farmgate price	USD/kg	0.32	0.35	0.40

The results of the solar water pump analysis (Table 4B) demonstrate that in the case of the solar water pump being used to irrigate maize, the farmer's decision to cultivate crops for two harvests in a year or only one has the largest impact on the financial viability of the pump. The base case, mono-cultivation, assumes that the farmer grows maize during the rainy season as well as in the dry season by virtue of having access to irrigation. The farmer would need 2.35 years to recover the initial capital expense of the pump. Yet if the farmer opts for growing maize in the rainy season, but instead grows a cash crop (in this case tomatoes) in the second season (referred to as the crop rotation scenario - rendered possible by the input of solar-powered irrigation), the financial attractiveness of the investment, both from the perspective of the farmer and the supplier, increases dramatically. The price that the farmer sells their irrigated crop (which is related to the quality of production, with irrigated crops generally being higher in quality) also has a substantial effect on the financial viability of the investment in the pump. If the farmgate price is increased to $0.40/kg from the baseline $0.32/kg, the CAPEX recovery period declines from 2.35 to 1.02 years. A reduction in the upfront price of the pump also

[12] In row 32 of the model, the user is asked to select an irrigation scenario. Users are presented with four options as follows:
- No: No second season irrigation. Thus only irrigation during rainy season
- Mono-cultivation: Two seasons of staple crop cultivation enabled by year-round access to irrigation.
- Crop rotation: Again year-round irrigation, but diversifying through one season with staple crop and the other with horticulture (tomato used as test case)
- Year-round horticulture: Again year-round irrigation, but no cultivation of staple crops, only horticulture (year-round horticulture only selectable in horticulture columns - P, AB, AQ & BE).

has a substantial impact on financial viability, albeit slightly less influential than the preceding two scenarios. Under the base case ($738 for a 120W pump) the CAPEX recovery period is 2.35 years, which declines to 1.59 years if the pump price is reduced to $500.

Table 4B: Results of input changes on payback period, NPV and IRR of a solar water pump for maize cultivation in Zambia[13]

Input	Parameter	Unit	Base case	Scenario 1	Scenario 2
Selected irrigation scenario	Payback period	Time	2 years and 4 months	3 months	n/a
	NPV	USD	$1,194	$20,399	$-3565
	IRR	%	41%	466%	n/a
Upfront cost of pump	Payback period	Time	2 years and 4 months	1 year and 11 months	1 year and 7 months
	NPV	USD	$1,194	$1,332	$1,432
	IRR	%	41%	52%	62%
Maize price margin	Payback period	Time	2 years and 4 months	1 year and 6 months	1 year
	NPV	USD	$1,194	$2,221	$3,728
	IRR	%	41	65	98

Table 4C: Inputs to illustrate scenarios of techno-economic viability of a mini grid-powered maize shelling machine in Zambia

Input	Unit	Base case	Scenario 1	Scenario 2
Realistic throughput per hour	kg/hour	500	700	900
Upfront cost of the machine	USD	$1,118	$900	$700
Mini grid tariff	USD/kWh	$0.3	$0.2	$0.1

In parallel, Table 4D demonstrates that changes to inputs pertaining to upfront cost of agro-processing equipment and the mini grid tariff have a modest impact on financial viability in the case of a mini grid-powered generic maize shelling machine. Throughput per hour, on the other hand, has a substantial impact, with the CAPEX recovery period declining to 1.19 years from 3.59 when the throughput per hour increases from 500kg to 900kg per hour. The shelling machine modeled here has a maximum theoretical throughput of 1,000kg per hour. This reveals that the closest as possible that a farmer or agro-processing entrepreneur can get to the maximum throughput of the machine, the better. We find, however, that in reality the real-life throughput

[13] Note that each scenario is modeled in isolation. In other words, each scenario change for each input is compared to the base case of that input.

reduces due to insufficient volumes of unprocessed crop available in the area surrounding the agro-processing machine.

Table 4D: Results of input changes on payback period, NPV and IRR of a maize shelling machine in Zambia

Input	Parameter	Unit	Base case	Scenario 1	Scenario 2
Realistic throughput per hour	Payback period	Time	3 years and 7 months	1 year and 9 months	1 year and 2 months
	NPV	USD	$740	$2,716	$4,638
	IRR	%	25	55	84
Upfront cost of the machine	Payback period	Time	3 years and 7 months	2 years and 11 months	2 years and 3 months
	NPV	USD	$740	$1012	$1212
	IRR	%	25	32	45
Mini grid tariff	Payback period	Time	3 years and 7 months	3 years and 5 months	3 years and 3 months
	NPV	USD	$740	$882	$970
	IRR	%	25	26	28

6. Discussion and implications

The role of agriculture for achieving renewable energy-centered sustainable development objectives

This paper conducted a granular analysis of the role of agriculture for achieving renewable energy-centered sustainable development objectives in rural Africa, with a (scalable) application to the country-study of Zambia. Specifically, it takes a WEFE Nexus angle in relation to the challenge of rural electrification and productive uses of energy, to show its great importance for energy access and rural development. This is key in sub-Saharan Africa, a region where agriculture is the crucial source of livelihoods for much of the population, where chronic poverty persists in various forms. Our analysis shows that to enable the achievement of different development goals (energy access, water access, food access, poverty reduction, environmental flows preservation and climate change adaptation and mitigation), it is important to jointly assess resources, infrastructure, and investment needs across these dimensions. This is because the feasibility of energy access solutions – a key enabler for the use of appliances that are crucial to achieve increased agricultural productivity and profitability – is tightly linked to the consideration of such agriculture-related productive uses.

Our analysis for the country study of Zambia shows that scenarios with increased ambition in expanding irrigation and agricultural productivity result in improved diffusion and economic feasibility of infrastructure to provide universal energy access while supporting productive uses of energy. This result would be hardly visible with either conventional characterization of energy demand (without a spatially granular and agricultural sector-explicit characterization) or with a top-down energy modelling approach focused on the centralized infrastructure. Specifically, we find that off-grid energy access solutions have much higher feasibility in the medium run when coupled with more ambitious targets of agricultural development because the critical demand density to make them rapidly cost-competitive is reached. Failure to acknowledge the importance of such cascading repercussions would likely result in lack of economic and financial viability to install such decentralized infrastructure, and in turn likely persistent energy poverty and economic stagnation.

Challenges and enablers for financing and implementation

Besides acknowledging the existence of such cross-sectoral synergies to achieving rural development, our study gives explicit consideration to the financial and business-model related issues that underpin the implementation of small-scale rural infrastructure. This is because, while policies are implemented at the national or provincial level, implementation takes place at a much more granular level, that of the individual farmer or – at most – at the community level. As the results of the techno-economic scenario analysis have shown, financial viability is substantially improved when farmers grow crops for two seasons (and even better when a cash crop is cultivated in the second season), when the upfront cost of the equipment is reduced, when the price that the farmer can sell their crop for is increased and when the throughput per hour of a processing machine is increased.

Policymakers have an important role to play in enabling the conditions to achieve these scenarios. Demand-side subsidies that lower end-user cost is a useful tool that policymakers have at their disposal. Similarly, pro-poor results-based financing or standard grant initiatives (such as the I*ncreased Access to Electricity and Renewable Energy Production* program[14]) incentivize suppliers to target underserved customers in hard-to-reach areas with equipment that is in line with the ability-to-pay of customers. Finally, the reduction or removal of import duties and value added tax on irrigation and agro-processing equipment lowers the overall cost base. A lever additional to end-user cost reduction is consumer finance schemes (such as pay-as-you-go or lease-to-own models) whereby customers pay for their equipment over time. Digital technologies and systems such as mobile money enable suppliers to transact seamlessly with customers and policymakers would be well advised to create favorable conditions for development of the mobile money

[14] https://www.fao.org/wood-energy/search/detail/en/c/1270618/

ecosystem, such as the reduction of taxes on mobile money payments. Agricultural extension programs that support smallholder farmers to sell their crops in downstream markets (where crop prices are higher), e.g. major towns, is a useful tool that policymakers can use in increasing farmers' crop prices and in turn the financial viability of the solar water pump irrigating the same crops.

Limitations and future research

Altogether, our research demonstrates how national-scale integrated modelling with an explicit focus on Nexus interlinkages allows for assessing locally relevant productive demand sources and investment needs, and their implications for sustainable development. Despite the substantial effort to integrate the interactions among sectors and to represent the financial constraints, besides the resource requirements and technological characterization, limitations remain. For instance, future research could investigate the relevance of clean cooking goals and their relevance for energy demand and rural solutions business models. Moreover, a better characterization of the uncertainty in the parameter space of both macro-trends (e.g. socio-economic transformations, climate change scenarios) and local market conditions (e.g. technology prices, crop prices, climate-related risk for agricultural production) would strengthen the policy relevance of the assessment carried out in this paper. Finally, the framework implemented in this paper does not have a dynamic representation of the river flow and storage. Hence, upstream-downstream and international responses of water withdrawal are not factored in. We justify this choice being our focus mostly on rural off-grid power generation, rather than on hydropower management and centralized electricity generation. Nonetheless, transnational water transfers within the same basin are considered boundary conditions.

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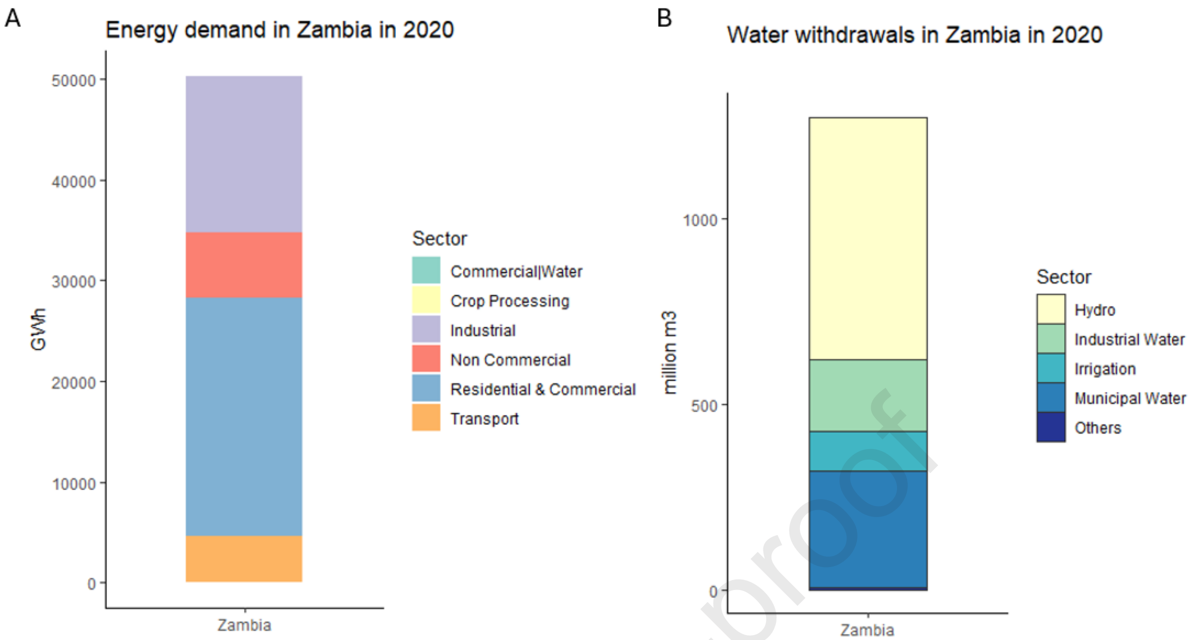
Conceptualization: G.F., A.V., A.T., M.T., G.I. Methodology: G.F., A.V., A.T., M.T., G.I. Software: G.F., A.V., A.T., M.T., G.I. Validation: G.F., A.V., A.T., M.T., G.I., A.Z. Formal analysis: G.F., A.V., A.T., M.T., G.I. Investigation G.F. Resources G.F. Data Curation G.F. Writing - Original Draft G.F., A.V., A.T., M.T., G.I. Writing - Review & Editing G.F., A.V., A.T., M.T., G.I., A.Z., E.B., M.H. Visualization G.F., A.V. Supervision G.F. Project administration G.F., M.H. Funding acquisition G.F., M.H.

Conflict of 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.

Data and code availability

The RE4AFAGRI platform is fully compliant with open-source code and open-data principles, with the objective of allowing users to replicate, adapt, and scale to other geographies and scenarios the analysis presented in this paper. A Github repository (https://github.com/iiasa/RE4AFAGRI_platform) hosts the source code of the modeling platform, which, in combination with the input data bundles hosted on the RE4AFAGRI Zenodo channel (https://zenodo.org/communities/leapre_re4afagri), allows to run the analysis from scratch with customized assumptions and data, or adapt it to other geographies.


A
Energy demand in Zambia in 2020
50000
40000
30000
20000
10000
0
GWh
Zambia
Sector
Commercial|Water
Crop Processing
Industrial
Non Commercial
Residential & Commercial
Transport
B
Water withdrawals in Zambia in 2020
1000
500
0
million m3
Zambia
Sector
Hydro
Industrial Water
Irrigation
Municipal Water
Others

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: