UNIVERSAL ENERGY ACCESS, AGRICULTURAL GROWTH, AND SUSTAINABLE LAND USE: ZAMBIA'S POLICY ROADMAP TO 2050

SUMMARY

This technical brief argues for the need of integrated land, energy and water resource use planning for achieving the Zambia National Energy Compact's ambitious targets of domestic production of maize, wheat and soybean. By using the CLEWs modelling framework, we show that the least-cost pathway for achieving the targets includes the mechanization of agriculture, with rainfed farming covering 24.7% of the abovementioned crops' harvested area by 2050, and irrigated commercial-scale covering 19.8%. This increases the pressure on groundwater resources (by more than 1,000% increased use) and the need for electricity for pumping (by 0.85 GW by 2050), highlighting the need for infrastructure planning and for diversification of the primary supply. Solar PV can be a low-cost option for supporting the electrification of irrigation while contributing to the Integrated Resource Plan's targets of 33% non-hydro renewable electricity supply by 2050.

1. INTRODUCTION

The electricity demand for agriculture in Zambia is projected to grow by the Ministry of Energy from 1,200 MW in 2030 to 3,625 MW by 2050, driven by ambitious goals of increased production of wheat, maize, and soybean output. This trajectory underscores the urgent need to align energy planning with agricultural growth, as outlined in the **National Energy Compact**, the **Integrated Resource Plan (IRP)**, and the **8th National Development Plan**. Yet, expanding agriculture and energy access will also reshape Zambia's land use patterns. Large-scale irrigation, renewable energy installations, and agro-energy zones will require careful spatial planning to balance competing demands for farmland, forests, mining, and conservation areas. Integrating land use considerations into energy–agriculture strategies is therefore essential to ensure that this expansion supports food security, climate resilience, and sustainable resource management. This calls for alignment with the **National Land Policy** under the Ministry of Lands and Natural Resources, which provides the framework for equitable land allocation, tenure security, and sustainable land management.

Achieving universal access to electricity by 2030 will require the accelerated deployment of distributed renewable energy (DRE) technologies such as mini-grids, solar home systems, and productive-use applications that complement grid expansion and directly support rural transformation. Anchored in the **National Energy Policy**, the Rural Electrification Master Plan (REMP), and Zambia's SDG 7 commitments, decentralized energy systems will be critical to closing the urban-rural access gap while powering households, schools, health centers, and agro-processing enterprises.

At the same time, expanding generation infrastructure to reach 10,000 MW by 2030 is central to Zambia's energy security and climate resilience strategy, together with a diversification of the low-carbon generation portfolio. The National Energy Compact sets a target share of non-hydropower renewables of 33% by 2030. Diversifying beyond hydropower through solar, wind, biomass, geothermal, and small hydropower projects will strengthen the resilience to hydrological shocks and stimulate green industrialization. Fast-tracking renewable energy feed-in tariffs, operationalizing a national renewable energy fund, and embedding renewable solutions within agricultural value chains will be essential to achieving this ambition, in line with the National Energy Policy and the IRP. The mobilization of investments may be guided by least-cost options, supported by blended financing frameworks that de-risk private capital and modernize the grid, as emphasized in the **Renewable Energy Strategy and Action Plan**.

Collectively, these priorities demand stronger coordination across the Ministry of Energy, Ministry of Green Economy and Environment, Ministry of Agriculture, Ministry of Lands and Natural Resources, Ministry of Water Development and Sanitation, Ministry of Infrastructure, Housing and Urban Development, and Ministry of Local Government and Rural Development, to harmonize policies that link energy access, food security, land use, and climate mitigation and adaptation objectives. Embedding climate resilience and

natural resource efficiency into infrastructure investment, alongside integrated monitoring across the IRP, Nationally Determined Contributions (NDCs), and the National Adaptation Plan (NAP) will ensure that Zambia advances toward universal access and sustainable energy for all.

2. ADDRESSING THE CHALLENGES

Zambia faces several critical challenges in reconciling sustainable land use management with rising agricultural electricity demand (whose share in the national demand is expected to grow from the current 2% to 33% in 2050), universal energy access goals, and the need for climate-resilient generation expansion.

First, the projected growth in crop production and rural electrification will intensify the pressure on the energy system, as highlighted in the Integrated Resource Plan, which identifies agriculture, mining, and industrialization as main drivers of future electricity demand.

Second, the current hydropower-dominated mix accounts for more than 80% of electricity generation. However, hydropower electricity generation might be threatened by increased seasonal variability in rainfall patterns. The World Bank has forecasted that the consecutive number of dry days with respect to historical values (143 average annual days) might increase by 6 days for 2020–2039 and by 9 days for 2040–2059 under a SSP1-2.6 climate change scenario (i.e., the best-case scenarios and thus the least likely). These conditions will progressively increase Zambia's energy system's vulnerability to droughts, with cascading consequences. Despite the targets set in the National Energy Policy to expand renewable energy sources and improve resilience, progress toward diversifying renewables and embedding them in the agricultural value chains remains slower than the rate of increase of these vulnerabilities, leaving always a gap.

Finally, weak institutional coordination across Ministries further undermines coherent planning. Without integrated action, Zambia risks falling short of its commitments to food security, universal electricity access, and low-carbon development, as emphasized in the National Energy Compact and Zambia's **Nationally Determined Contribution**.

3. APPROACH AND SCENARIO DEVELOPMENT

This study aims to shed light on the resource use implications of the ambitious domestic production targets for three of Zambia's largest crops (wheat, maize, and soybean) and how access to distributed non-hydro renewable energy may act as enabler of agricultural development. We employ the Climate, Land, Energy, and Water systems (CLEWs) modeling framework to analyze Zambia's agricultural transformation and energy transition pathways, jointly, under a cost-minimization perspective. CLEWs provides an integrated systems approach that captures the interdependencies between energy demand, agricultural production, land use, and climate resilience. By linking sectoral models, the framework enables coherent policy analysis that reflects trade-offs, synergies, and long-term sustainability outcomes.

Many countries have adopted the CLEWs modelling framework as a decision-support tool. For example, Ethiopia used CLEWs to guide its Climate-Resilient Green Economy Strategy by evaluating trade-offs between hydropower expansion and irrigation (Tesfaye et al., 2021). Kenya applied CLEWs to examine synergies between agriculture, energy, and water access under climate change scenarios (Mwango et al., 2026). Costa Rica created a CLEWs modelling ecosystem that supported several policy cycles, studying among others job creation implications from the country's transition to net-zero emissions (Sauma Chacón et al., 2023).

The United Nations Department of Economic and Social Affairs (UN DESA), KTH Royal Institute of Technology, and the University of Zambia ran a UN DESA-funded 1-year program where a large group of analysts from various governmental institutions, research organizations, and utilities in Zambia were trained in the use of CLEWs modelling. The group jointly created a CLEWs model infrastructure for Zambia and designed scenarios to deliver insights on key policy questions for the country's long-term integrated resource planning.

3.1. Scenario Development

We analyze three questions related to policy priorities brought up by the program participants.

Q1. What implications do the National Energy Compact's 2030 and 2050 targets for crop production have for investment in and planning of land, water and electricity supply in Zambia?

We designed for this the AgriBoost scenario, which implements the domestic production targets of 10 million tons of maize by 2050 (+212% compared to 2023), 3 million tons of soybeans (+349%) and 15 million tons of wheat (+4350%).

Q2. What role can distributed solar PV have in supporting the achievement of the maize, soybean and wheat production targets?

We designed for this the AgriBoostPlus scenario, which stems from the same assumptions as AgriBoost, but it assumes that any increase of irrigation is electrified only via off-grid solar PV panels and assesses the costs of such pathway against the baseline of AgriBoost.

Q3. Are there synergies between the IRP's target of 33% non-hydro renewables in national electricity supply by 2030 and the enhancement of agricultural production?

The Green_Shift scenario stems from the same assumptions as AgriBoostPlus, and it investigates if solar PV is

among the least-cost technological options for increasing the share of non-hydro renewables in national electricity supply to 33% by 2030. This gives insights on whether electrifying irrigation via distributed solar PV may also be an enabler for reaching the IRP's non-hydro generation targets and, vice versa, whether the latter targets may create a more favorable environment for investments in solar PV in the agricultural sector.

3.2. Analytical Framework

Integrated Systems Optimisation. CLEWs links electricity generation, agricultural output, land use change, and water supply, quantifying the cross-sectoral impacts of different policies under a least-cost perspective, while taking into account resource constraints. One key methodological choice was to separate the land area of the country into 3 agro-ecological zones, based on the average crop yields. This allows an optimal reallocation of agricultural land also across zones, based on actual yields and costs of production.

Policy Alignment. The scenarios are benchmarked against Zambia's Integrated Resource Plan (IRP 2023-2053), National Energy Policy (2019), 8th National Development Plan, and National Energy Compact (AES 300) to ensure consistency with national targets.

Data Inputs. The key drivers in the model are the projections for electricity, food crops (maize, wheat, soy, and cassava) and water; the costs of electricity and agricultural production; the policy targets (as per scenario descriptions); and resource constraints (e.g., land availability, runoff and groundwater, primary energy resources). The data for the energy system representation is partly derived from CCG's Zambia Whole Energy System Model and then updated and calibrated for the reference year of 2023 based on the latest available update of Zambia's installed electricity generation capacity published by the Ministry of Energy. The calibration of land covers and uses, water cycle and agricultural yields stem from GAEZ v4.0 data and national statistics.

The technical description of the model, its boundaries and its structure, its datasets and all the data sources can be found on Zenodo.

4. POLICY RECOMMENDATIONS

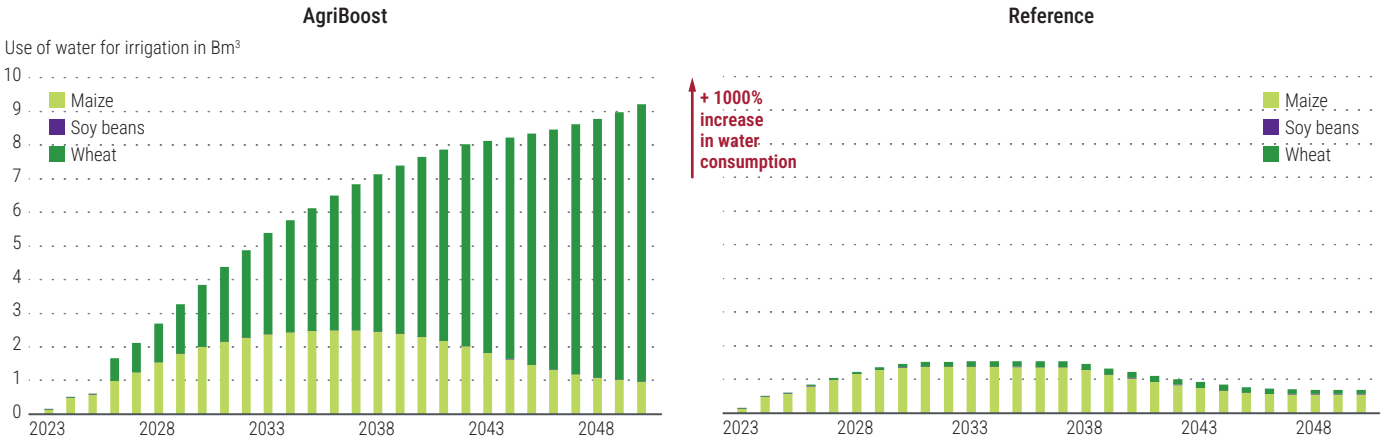
Q1. What implications do the National Energy Compact's 2030 and 2050 targets for crop production have for investment in and planning of land, water and electricity supply in Zambia?

The increase in crop production assumed in the AgriBoost scenario leads to a larger harvested area in each agro-ecological zone at the expense of grassland, more than quadrupling greenhouse gas emissions from 1.5 MT to 7 MT CO_2eq in cumulative land-use-change emissions from 2023 to 2050 when compared to the reference scenario. Production by 2050 increases by 73.6% and agricultural harvested area 71.2% (up to around 68,000 km2) with a shift from small-scale to commercial-scale agriculture and an increase in irrigation, which in turn boosts agricultural yields. The production of wheat, soybean, and maize moves to a large commercial-scale farming system, covering 24.7% of rainfed harvested area (16,800 km2) and 19.8% of the irrigated area (13,400 km2) by 2050, while small-scale farming is optimized to decrease from 90% of the total harvested area in 2023 to 13.1% by 2050.

Figure 1 shows that the increase of maize, wheat, and soybean production assumed in the AgriBoost scenario leads to significantly higher water use for agriculture, reaching 4.7 Bm³ by 2050 compared to 0.4 Bm³ in the reference scenario. According to Zambia Development Agency, the country is already utilizing 54% of the available renewable water resources (the availability accounts for 86.6 billion m3 of surface water and 57.4 billion m3 of groundwater).

Figure 1

Use of water for crop irrigation in the AgriBoost scenario (featuring the National Energy Compact's production targets for maize, wheat and soybean) vs the Reference scenario (no targets)



The envisaged agricultural boost is forecasted to be supplied primarily from groundwater recharge (under average precipitation conditions).[1] According to **CMIP6 projections**, future climates are not forecasted to alter significantly the average annual precipitation, making it feasible for the country to keep the boost in water needed for irrigation considering its groundwater reserves. However, future studies should focus on understanding if there is an impact in seasonal water recharge, given the aforementioned increase in the consecutive dry days that might create imbalance in the hydrological cycle. Moreover, the use of groundwater results in proportionately larger electricity consumption for water pumping. Irrigation mostly supplies the large increase in wheat production (over 40 times in 2050 compared to 2023). Overall, the energy requirements increase 12 times and water requirements 13 times compared to those in the reference scenario to achieve the necessary productivity boost.

The higher production of wheat, soy, and maize results in a 17% cumulative capital cost increase in the time horizon 2023–2050 and a 22% increase in direct CO_2eq emissions. The rise in crop production leads to a total installed power supply capacity of 9.62 GW by 2030 compared to the 9.45 GW in the reference scenario because of the increased energy required for pumping water for irrigation. Medium-scale hydropower combined with utility-scale solar PV emerges as the most cost-effective mix for electricity supply.

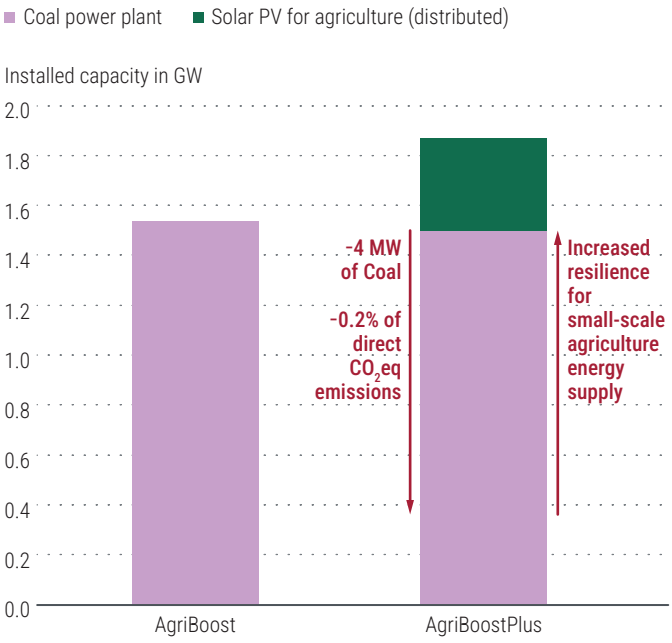
Recommendation: Create coordinated (policy and regulatory) support for investments in mechanization, extension of electricity access, and surface-based irrigation for both small- and commercial-scale farms to achieve the ambitious targets of increased wheat, maize and soybean production. The least-cost path to achieving the targets includes extension of irrigated harvested area (3,670% increase) and industrialization of agriculture (700% increase in commercial-scale agriculture). This increases the pressure on groundwater resources (1,246% increase), currently the most used source of irrigation, and requires electricity that is not currently available in many farms. Failing to account for these cross-sectoral feedbacks will delay the agricultural development and undermine the achievement of the domestic production targets.

Q2. What role can distributed solar PV have in supporting the achievement of the maize, soybean, and wheat production targets?

The introduction of distributed solar PV for pumping water in small-scale agriculture reaches 0.37 GW of installed capacity in the AgriBoostPlus scenario (Figure 2), reducing by 4 MW the installed capacity of coal power plants.

Figure 2

Differences in installed capacity and CO2eq emissions between AgriBoost and AgriBoostPlus scenarios



The increased access to electricity and irrigation carries the potential to mitigate the exposure of small-scale farming to prolonged droughts, although it shifts the dependency on water from rainfall towards groundwater.

Recommendation: Support the upscaling of distributed solar PV as a low-cost enabler to power water pumping for irrigation in small-scale agriculture, which increases small-scale agriculture's energy supply resilience to droughts. The introduction of distributed solar PV has a marginal impact on GHG emissions, cutting CO2eq direct emissions by 0.2% by 2050 and a 3% cumulative capital cost increase over the time horizon 2023–2050.

Q3. Are there synergies between the IRP's target of 33% non-hydro renewables in national electricity supply by 2030 and the enhancement of agricultural production?

Achieving the target of 33% non-hydro renewables (GreenShift scenario) reduces the risk of greater resource stress and vulnerability to climate change by reducing the dependence on water. The least-cost electricity mix to reach the target (while considering also the large targeted increase of wheat, maize, and soybean production) implies increasing the installed capacity of utility-scale, grid-connected solar PV by 25%, distributed solar PV to 260 MW, and onshore wind to 3,500 MW by 2030, while reducing by 19% the installed capacity of medium-size hydro power (See Figure 3). This enhances the system's resilience to climate shocks and mitigates land-use-change impacts, creating a 24% reduction in direct CO_2eq emissions by 2050 compared with the AgriBoost scenario (thanks to the reduced use of

1 In the CLEWs model, only the surface water and groundwater recharges from the year's precipitation can be tapped into. If dry scenarios were modelled, such increase of water withdrawal might become constraining.

coal). Additionally, it shows that grid-connected and distributed solar are low-cost enablers of increased agricultural production. The faster non-hydro renewable roll-out by 2030 and the adoption of onshore wind reduce the reliance on coal by 26% by 2050 compared to the AgriBoost scenario. Further, distributed solar PV upscales to a total of 2.43 GW of installed capacity by 2050. As for the AgriBoostPlus scenario, of these 2.43 GW, 370 MW are allocated exclusively to small-scale farming, enabling its expansion.

Recommendation: Deploy utility-scale solar PV by 850 MWand onshore wind by 3,500 MW in addition to distributed solar PV to synergize between the IRP's target and the enhancement of agricultural production. Supporting the boost in agricultural production with a faster non-hydro renewable roll-out by 2030 can: (1) contribute to the electrification of farming; (2) mitigate the impact on climate change; (3) adapt both agricultural and electricity production to the forecasted climate change hazard. Grid-connected and distributed solar PV emerge from this scenario among the lowest-cost, non-hydro options for diversifying the supply and building climate resilience while meeting the targets for increased agricultural production.

5. FINAL CONSIDERATIONS AND FUTURE STEPS

According to the IRP, the electrification of the agricultural sector will consist mostly in the industrialization of the whole production chain. The electrification of the water supply for irrigation has a minor impact on the national electricity needs per se, but it bears implications for infrastructure planning. The use of distributed solar PV represents a low-cost alternative for electrifying irrigation for small-scale farming. Future work will look at extending the representation of the agricultural sector in the model to capture all uses of energy and water in the whole production chain (including also livestock and processing of agricultural products). It will also include improving the accuracy of emissions representation through a dedicated GHG inventory, enabling more robust assessment of production-driven impacts. Coupling the CLEWs model with geospatially explicit electrification models could enhance the representation of the energy system and provide more insights on the respective roles of grid-connected or off-grid solar PV in electrifying agriculture. Finally, further analysis is needed to evaluate the risks associated with expanded groundwater-based irrigation and the resulting water resources stress under climate change.

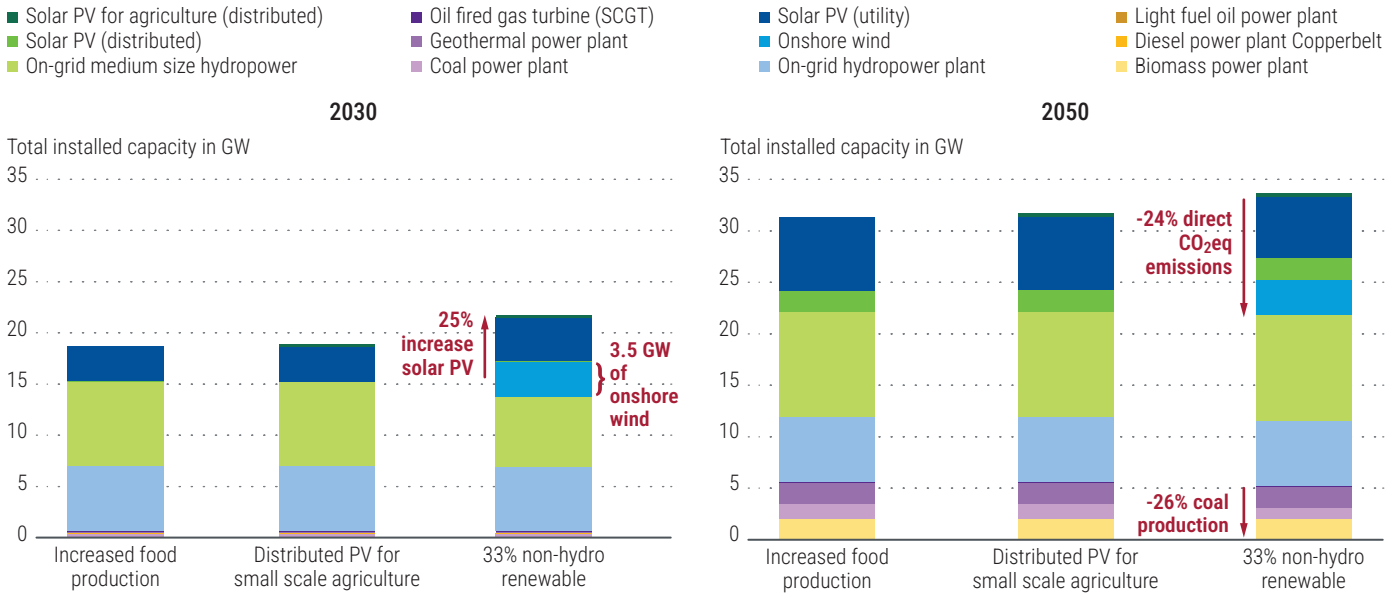
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Figure 3

Total installed capacity (GW) across all scenarios



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