

TOWARDS RESILIENT AND INCLUSIVE CLIMATE COMPATIBLE DEVELOPMENT: A PARTICIPATORY, MIXED-METHOD SCENARIOS APPROACH FOR ZAMBIA

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ABSTRACT

Climate compatible development aims to align climate change mitigation and adaptation with social and economic development. Successful climate compatible development must be socially inclusive, and resilient to external shocks. Zambia is a country at the frontline of climate change, with multiple development challenges, and ambitions to pursue a climate compatible development pathway. Scenarios are tools with a long history of application in strategic planning, and may be suitable tools to help countries explore climate compatible development. Therefore, we developed a novel participatory, mixed-method scenario process, to explore pathways of resilient and inclusive climate compatible development for Zambia. We took a stakeholder-led participatory approach, and combined qualitative scenario development techniques with quantitative energy system modelling. We compared a scenario characterised by centralised governance and infrastructure, large-scale export-led industries and continued urbanisation, with one characterised by greater decentralisation of governance, investment decisions and economic development strategies, which maintains the viability of rural livelihoods and slows the urbanisation trend. The scenarios provide a framework for considering opportunities and risks in planning for climate compatible development, and suggest that Zambian decision-makers should: test infrastructure investments and long-term economic plans for both climate and economic resilience; pursue mutually beneficial, equitable development partnerships with like-minded international partners; and appropriately allocate responsibility to different scales of governance and ensure coordination between them. The issues highlighted by the scenarios are of relevance to other countries facing similar challenges. The paper demonstrates that a participatory, mixed-method scenario approach provides a useful framework to explore climate compatible development.

1. Introduction

Climate change “has led to widespread adverse impacts ... and

related losses and damages to nature and people” (IPCC, 2023, p. 42). The injustice of the climate change problem is compounded by the fact that “vulnerable communities who have historically contributed the

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least to current climate change are disproportionately affected” by it (IPCC, 2023, p. 42).

The importance of addressing both climate change mitigation and adaptation, whilst also delivering social and economic development, especially in low- and middle-income countries (LMICs), has led to calls for a synergistic model of “climate compatible development”, which aligns each of these objectives (Mitchell and Maxwell, 2010).

However, the persistent and long-term development and climate adaptation challenges of many LMICs have been further exacerbated in the last few years by global shocks, including the COVID-19 pandemic and Russia’s invasion of Ukraine. The economic impacts of such shocks have contributed to debt defaults in many LMICs, increasing global inequality (Mahler et al., 2022, UN, 2023) and further depleting the ability of LMICs to address climate change and meet development objectives (World Bank, 2023).

To be successful, climate compatible development must be inclusive – achieving broad-based development, in particular meeting the needs of those least well-off; but it must also be resilient, to avoid being derailed by external shocks of the kind witnessed in recent years (Friedman, 2023).

Resilient and inclusive climate compatible development cannot be achieved by reactive, short-term actions. It requires a holistic and long-term strategic planning approach. There is a rich literature that can inform this kind of holistic planning approach, in the diverse tradition of strategic scenario development (de Jouvenel, 1967, Kahn and Wiener, 1967, Wack, 1985b, Godet, 1987, Schwartz, 1991). The use of scenarios for strategic planning has been theorised and practised in a wide variety of contexts (Bradfield et al., 2005, Hughes et al., 2013), and has potential to support creative approaches to considering resilient and inclusive climate compatible development.

This paper reports on a participatory, mixed-method scenarios and energy modelling exercise, carried out to explore the prospects for resilient and inclusive climate compatible development in Zambia. Zambia is at the frontline of climate change, being recently affected by severe droughts (Chisalu, 2024). It was also affected by inflation and increased debt following recent global economic shocks (Mbewe et al., 2024). It has multiple development challenges, including in relation to education, poverty and access to basic services (Table 1). But it also has also declared ambitious greenhouse gas reduction targets (GRZ, 2021), and launched a “Green Growth Strategy”, which aims to pursue “resilient and climate compatible growth” (MoGEE, 2024, p. 40) alongside “improved inclusivity” (MoGEE, 2024, p. 52). It is therefore a highly relevant country in which to consider the prospects for resilient and inclusive climate compatible development. The participatory scenarios process adopted in this paper, and its outcomes, also generate learning for other countries with similar challenges and ambitions.

The quantitative modelling part of our scenario process focusses on the energy sector, because of its role as a keystone sector connecting economic and social development, and climate change and the environment. Globally, the energy sector is the dominant source of greenhouse gas emissions (IPCC, 2022, p. 7). As LMICs develop, their energy demands will become greater, with corresponding effects on emissions, if a climate compatible pathway is not pursued. In Zambia, energy also links to greenhouse gas emissions and economic activity through deforestation caused by the harvesting of wood and charcoal for cooking (GRZ, 2021, p. 9). Zambia’s energy system is also directly affected by climate change, due to the impact that droughts have on the output of hydro power (Mukeredzi, 2024). Thus, in Zambia, energy can rightly be thought of as “the golden thread that connects economic growth, social equity, and environmental sustainability” (Ki-moon, 2012). Our quantitative energy modelling focus acknowledges the criticality of this sector to climate compatible development, while the broader qualitative components of the scenarios place the energy sector within a holistic understanding of the links between energy and land use, water, the economy and wider society.

The paper makes the following contributions:

Table 1

Zambia country statistics. Data sources: ⁱWorld Bank World Development indicators (World Bank, 2024); ⁱⁱIEA Energy Statistics (IEA, 2024); ⁱⁱⁱEnergy Regulation Board (ERB, 2023) ^{iv}Zambia Extractive Industries Transparency Initiative (ZEITI, 2023); ^vILO (ILO, 2024); ^{vi}World Population Review (WPR, 2024).

Electricity access, 2021 ⁱ	Urban: 86 % Rural: 15 % Average: 47 %
Access to clean fuels and technologies for cooking, 2021 ⁱ	Urban: 20 % Rural: 2 % Average: 10 %
Primary energy supply, 2021 ⁱⁱ	Biomass: 72 % Oil: 12 % Hydro: 12 % Coal: 4.0 % Solar PV: 0.11 % Hydro: 88 % Coal: 11 % Solar PV: 0.73 % Oil: 0.012 %
Electricity supply, 2022 ⁱⁱⁱ	Exports: 72 % Government revenues: 44 % Contribution to GDP: 9%
Contribution of extractive industries, 2022 ^{iv}	Share of population 1973: 33 % Share of population 2022: 46 %
Urban population ⁱ	Share of population: 61 % Share of population: 20 % Share of total employment: 86 %
Primary education attainment, 2018 ⁱ	Share of population: 61 %
Upper secondary education attainment, 2018 ⁱ	Share of population: 20 %
Informal employment, 2022 ^v	Share of total employment: 86 %
Extreme poverty, 2015 ⁱ	Share of population: 61 %
People using at least basic sanitation services, 2022 ⁱ	Share of population: 36 %
Intra-country inequality, 2015 ⁱ	Gini index: 56 %
Country ranking for inequality, most recent available data for all countries ^{i,vi}	Gini index, ranked high to low: 4th highest

- It provides Zambian decision-makers with a scenario framework to support strategic planning for resilient and inclusive climate compatible development, and makes recommendations on policy and governance
- It raises issues and makes recommendations that are also of relevance to other countries facing similar challenges, and with similar ambitions, as Zambia
- It adds to the literature on mixed-method and participatory scenarios by describing a novel methodological approach combining stakeholder-led scenario development, with an open-source energy modelling framework. The approach described here could be taken up by other countries, groups or communities interested in exploring what resilient and inclusive climate compatible development could mean for them. In particular, there are relatively few mixed methods scenario studies that focus on LMICs. This paper addresses that gap, leading to methodological and empirical lessons for other LMICs.

The remainder of the paper is structured as follows. Section 2 provides relevant background context on Zambia. Section 3 describes the theoretical framework for our scenarios process, referring to the scenario development literature, and Section 4 describes the steps of our novel scenario method. Section 5 presents the scenario results, and Section 6 discusses the policy and governance implications of our scenarios process, as well as reflecting on limitations and next steps. Section 7 concludes.

2. Context

Table 1 provides a statistical snapshot of Zambia. As the table shows, Zambia faces multiple development challenges. Access to modern energy services is low, with domestic cooking being particularly reliant on wood and charcoal (World Bank, 2024). The electricity system is

dominated by hydro power (ERB, 2023), and the economy is strongly dependent on large-scale mining, especially copper (ZEITI, 2023). The majority of people living in rural areas are engaged in small scale farming, and most work is undertaken in the informal sector (ILO, 2024). There are low completion rates of secondary education, low access to health and sanitation, and high levels of poverty and inequality (World Bank, 2024, MoF, 2022).

Zambia is vulnerable to climate impacts. Severe droughts occurred in what should have been the rainy seasons of 2015–2016 and 2019–2020, which doubly impacted the economy through reducing agricultural production and curtailing energy output from the hydro-dominated electricity generation system (AICCRA, 2023). The rainy season of 2023–2024 was once again subject to extreme drought, leading the President to declare on 29th February 2024 “the prolonged dry spell as a national disaster and emergency”, while announcing the need for energy rationing and calling for international humanitarian food support (Chisalu, 2024, p. 2,7).

The economic impacts of the COVID-19 pandemic exacerbated the effects of several years of high borrowing to fund infrastructure projects, causing debt and repayment rates to spiral to unsustainable levels. Zambia declared a debt default in November 2020 (Mbewe et al., 2024), and in 2022 obtained an extended credit facility from the IMF, under the terms of which it is undergoing economic and fiscal restructuring (IMF, 2023).

One of the major themes of recent Zambian political discourse is the concept of decentralisation. Interest in decentralisation as a general governance principle can be traced back to the years immediately following Zambia’s independence from the British Empire, achieved in 1964 (Cabinet Office, 2023), but was given renewed emphasis in 2021 when President Hichilema targeted “decentralisation and devolution of various central government functions... that will be better managed at the local level with appreciation for local challenges” (Hichilema, 2021, p. 37). Following this, a new version of the National Decentralisation Policy was published in 2023, seeking to enable “citizen participation in achieving sustainable development and enhanced service delivery” (Cabinet Office, 2023, p. 2).

Zambia hopes to pursue an “export-led trade strategy” (Hichilema, 2021, p. 21) in electricity generation, mining and manufacturing, as well as in agriculture, the output from which it is hoped will increase to the extent of not only addressing domestic food security, but so that Zambia will become “a breadbasket for the region” (Hichilema, 2021, p. 12). Zambia operates a dual land tenure system, with “stateland” being available for private leasehold tenure, while “customary” land is administered by Traditional Leaders – Chiefs and Chieftainesses. The Eighth National Development Plan targets ambitious scaling up in production of key sectors, including to more than double agricultural production by 2026 and to more than triple copper production by 2032 (MoF, 2022).

3. Theoretical framework

Scenarios are descriptions of possible future outcomes, developed to support decision-making in respect of the uncertain and undecided future (Wack, 1985a, Volkery and Ribeiro, 2009, Hughes, 2013). Scenario methods are diverse, reflecting the vast range of future-oriented questions to which they have been applied in both business and public policy contexts (Bradfield et al., 2005, Volkery and Ribeiro, 2009, Cordova-Pozo and Rouwette, 2023). In this section we situate our scenario framework and methodological approach in relation to existing scenario literature.

Scenario typologies commonly identify a methodological distinction between “exploratory” and “normative” scenario styles (van Notten et al., 2003, Börjeson et al., 2006, Kosow and Gaßner, 2008), where the former considers what *could* happen, and the latter considers what *should* happen. We use scenarios to explore how resilient and inclusive climate compatible growth may successfully be achieved in Zambia –

hence our approach is primarily normative in orientation. However, to avoid the risk of drifting into mere “wishful thinking”, our approach ensures that the scenarios are not disconnected futures, but are grounded in the actual present, and describe “a hypothetical sequence of events that could lead plausibly to the situation envisaged” (Kahn and Wiener, 1967, p. 262). Scenarios should also be tested for their resilience against “dominating” external risks and threats, which actors within the system cannot control, but which can be adapted to (de Jouvenel, 1967, pp. 52–53; Hughes et al., 2013).

Another distinction often found in scenario typologies concerns their use of quantitative (such as techno-economic modelling or input–output tools) or qualitative (such as interviews, role plays, policy or political analysis) methods (Huss and Honton, 1987, van Notten et al., 2003, Bradfield et al., 2005, Kosow and Gaßner, 2008). However, mixed qualitative and quantitative approaches, which coherently organise a variety of “economic, technological, competitive, political, and societal information” (Wack, 1985a, p. 146), also have a long pedigree in scenario literature. Mixed-methods are particularly relevant in scenarios concerned with environmental change, due to the relevance not only of physical and technical factors, but also of social and political factors, to such topics (Hughes and Strachan, 2010; Hughes, 2013). Recent years have seen growing numbers of sustainability transition scenarios pursuing mixed-method approaches (Alcamo, 2008), in studies of future electricity (Geels et al., 2020), transport (Venturini et al., 2019) energy systems (Fortes et al., 2015) and energy justice (Gladkykh et al., 2021). McDowall (2014) proposes an iterative mixed-method approach, where the qualitative and quantitative methods come into “dialogue”, to develop a coherent set of qualitative narratives and quantitative modelling results. Mixed-method scenario approaches have been under-used in energy transition research applied to African countries (Blimpo et al., 2023). This is a research gap that this paper aims to fill.

We took a participatory approach to co-creating the scenarios with relevant stakeholders, on the basis that good scenarios must connect with the “deepest concerns” of their intended users (Wack, 1985b, p. 87), as well as their aspirations. A classic example of a participatory approach is the “Mont Fleur” scenarios process, undertaken in post-apartheid South Africa (Le Roux and Maphai, 1992). Other literature describes the involvement of public and private organisations, academics and industry practitioners in scenario development (Venturini et al., 2019, Lovell et al., 2022, Robertson et al., 2017).

Thus, in relation to scenario literature, our approach can be located as normative, mixed-method and participatory.

4. Methods

Based on the theoretical framework and principles established in the previous section, we developed a scenario process consisting of five stages, and informed by four intuitive guiding questions, as illustrated in Fig. 1.

The four guiding questions are considered at each stage of the process. The first three of these questions have clear similarities to a framework described elsewhere as the “three horizons” approach (Sharpe et al., 2016; López-Rodríguez et al., 2024) – but they also emerge from the theoretical framework described in the previous section. We ask “where are we now?” because it is important to ground scenarios in the actual present. In our case, this involved identifying challenges and barriers to resilient and inclusive development in Zambia today. We ask “where do we want to be?” because the purpose of normative scenarios is to make the future better than it otherwise might have been. In our case, this meant imagining what Zambia would look like if today’s challenges and barriers were overcome through a process of resilient and inclusive climate compatible development. We invited stakeholders to look as far ahead as the year 2063, aligning with the time horizon of the African Union Agenda 2063. We ask “how do we get there?”, because scenarios are not merely an exercise in wishful thinking about dislocated futures, but should show a clear pathway from the

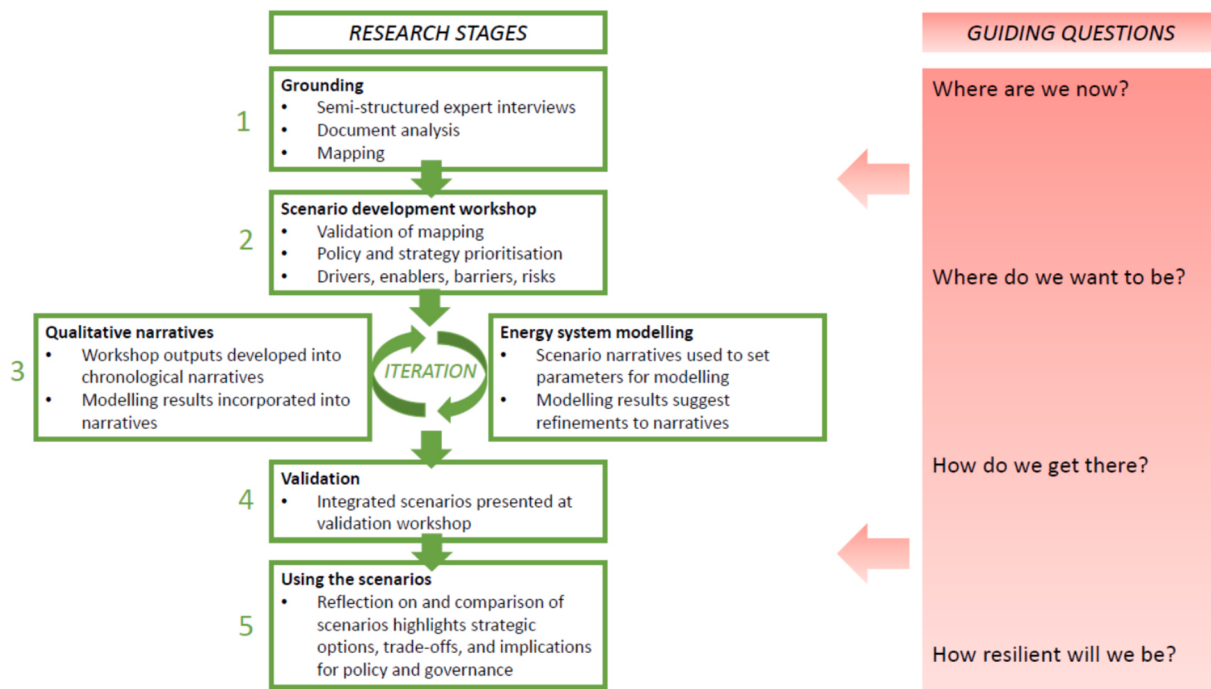


Fig. 1. Schematic diagram of research stages and guiding questions for scenario process.

present to the future. In our case, this involved identifying strategies and policies that would facilitate a transition from today's system to the imagined desirable future system.

We also ask a fourth question, “how resilient will we be?”, because it is important to acknowledge that the future is not only dependent on things that we can control, but may also be affected by external risks and threats that lie beyond our control (Hughes et al., 2013). In our case, this involved identifying risks such as climate impacts and economic uncertainties.

The first stage (1) was to ground our scenarios process in relevant context. Semi-structured interviews were conducted with 27 key expert informants in Zambia between April and July 2021. Participants were purposively identified based on their experience and level of seniority within relevant fields, and included stakeholders from Zambian government ministries and agencies, financial organisations, NGOs, research and academic sectors, religious organisations, the private sector, multilateral institutions and foreign aid agencies (Appendix A). This process was supported by a literature review of key policy documents, undertaken during the same period (Nyambe-Mubanga et al., 2023). The material was thematically analysed and organised for its relevance to each of the four guiding questions shown in Fig. 1. This resulted in a mapping of concerns, aspirations, and potential governance approaches, according to Zambian stakeholders and key policy documents, as a basis for potential scenarios. This mapping is described in more detail in Nyambe-Mubanga et al. (2023) and Appendix B.

The mapping of concerns, aspirations, and potential governance approaches, was presented at a three-day stakeholder workshop in Lusaka, Zambia, in December 2021 (2). Participation was limited to 17 participants from the abovementioned organisations, due to Covid restrictions. After refining and validating the mapping (Appendix B), stakeholders were invited to identify more specific policies and strategies that would be required to bring about desired futures within alternative governance approaches, and furthermore to attempt to prioritise the strategies, leading to emerging chronological scenarios. Finally, the stakeholders were asked to identify key drivers and enablers, barriers and risks, for the various strategies and for each scenario overall. The results of this process are described in more detail in Mapulanga et al. (2024) and Appendix C.

Thus, the workshop results provided coherent scenario outlines, each associated with a prioritised list of specific policies, strategies and other enabling factors. The project team developed this material into full chronological scenario narratives (Appendix D) during the early months of 2022.

The next stage was to add quantitative detail to the scenarios. The focus for quantification was the energy sector, due to its critical interconnections with climate compatible development, as explained in Section 1. Aligning the qualitative scenario narratives with the quantitative modelling required an iterative process (3) that took place between March and August 2022.

The energy system model OSeMOSYS-Zambia was developed, covering all major sectors of the Zambian energy system (OSeMOSYS, 2024; Howells et al., 2011; Hofbauer et al., 2024; Hofbauer, 2024). The model was calibrated based on the Zambian national energy balance for 2018 provided by the European Environmental Bureau, with reference energy service demands, economic and technological drivers projected based on the best available data (Allington et al., 2022; Tembo et al., 2020; Appendix E).

While 2063 was used as the furthest horizon in the workshop discussions, the more detailed parts of the qualitative narratives focussed on plotting the path from the present through to the 2050s. The use of a modelling horizon of 2050 also facilitated the use of several publicly available datasets for important modelling parameters, as described in Allington et al (2022). Therefore, the scenario and modelling descriptions reported in this paper focus on the period between now and roughly the middle of the century.

The modelling begins with a default or “reference” scenario, which essentially maintains historical trends, and prioritises least-cost solutions to meeting projected energy demands. Whenever an element of one of the scenario narratives suggests that it would diverge from these reference assumptions, adjustments are made to modelling input parameters or constraints to reflect the particular conditions of the scenario. For example, a scenario assumption of increased energy access relative to continued trends, would see corresponding increases in the model's energy service demands, relative to the reference scenario. An additional scenario assumption of greater energy efficiency would in turn moderate this demand growth. This accumulation of modelling

adjustments results in the gradual development of a quantitative energy system representation of each scenario.

The emergence of the quantified model runs could also feed back information to the qualitative narratives, increasing their precision or even bringing in elements that had not been considered, but which had been shown by the modelling to be significant. For example, the qualitative narrative of the Decentralised scenario mentions off-grid renewable hubs. This required interventions on the model to push greater contributions from off-grid technologies such as solar. As a result of this intervention, the model selected greater amounts of energy storage to contribute to energy balancing. This effect can be seen in the Decentralised modelling results, and is reflected in the Decentralised narrative. Conversely, the modelling of the Centralised scenario was less constrained on electricity technology choice, and built more large-scale electricity generation technology, including large hydro and gas. This specific technology mix is also an output of the model, and was re-incorporated into the scenario narratives. Similar examples of this “conversation” between the scenario narratives and the model took place in relation to each energy sub-sector. More detail on this process is provided in [Appendix E](#).

This process resulted in integrated qualitative-quantitative scenarios. The scenarios were presented at a final validation and dissemination event in February 2023, giving stakeholders the opportunity to comment on and make refinements to the integrated scenarios (4).

Finally, we reflected on and compared the scenarios to consider their implications for policy and governance (5), as reported in the Discussion (Section 6) of this paper.

5. Results

This results section is structured to reflect the four guiding questions represented in [Fig. 1](#). Section 5.1 summarises stakeholders’ answers to the guiding questions “where are we now?” and “where do we want to be?” Section 5.2 introduces and analyses the scenarios in order to explore “how do we get there?” Section 5.3 considers the scenarios in the context of potential risks, asking “how resilient will we be?”.

5.1. Stakeholder priorities and aspirations: Where are we now, and where do we want to be?

[Table 2](#) summarises the characterisation of current challenges and future aspirations as identified by stakeholders. More detail is provided in [Appendix B](#) and in [Nyambe-Mubanga et al. \(2023\)](#) and [Mapulanga et al. \(2024\)](#). As the table shows, stakeholders identified challenges relating to energy access, transport infrastructure and congestion, climate vulnerability of agriculture, sporadic economic growth and limited access to fundamental services. Looking forward, stakeholders expressed visions of a diversified, resilient and high-skill economy, with universal access to sustainable energy and fundamental services, climate resilient infrastructure, clean transportation and sustainable land use.

5.2. How do we get there?

Alternative scenarios were developed by extending emergent trends in current policy discourse, providing a framework to explore how the present reality could evolve along a trajectory of resilient and inclusive climate compatible development, towards the aspirations expressed by stakeholders. Detailed chronological narrative descriptions of the resulting scenarios are provided in [Appendix D](#). The essential characteristics of the two scenarios can briefly be summarised as follows:

In the Centralised scenario, the government seeks to create an enabling environment for international private sector investment in large-scale infrastructure. Mining diversifies beyond copper, and remains export-focussed. Mineral rents are used for social investments, targeting fast growing urban areas. Agriculture is increasingly large-scale, high-input and export focussed, as well as diversifying into

Table 2

Current challenges and concerns emerging from literature review and stakeholder consultations.

Sector	Current challenges	Future aspirations
Energy	• Low levels of access to electricity • Energy is unaffordable to many without subsidies • Charcoal and wood largely used for household cooking, which is connected with health impacts and deforestation • Electricity is dominated by hydro power, which is vulnerable to droughts • Challenges of remaining a low emission economy while developing	• Universal access to clean, sustainable and affordable energy • High energy efficiency in industry and other sectors • Develop renewable energy • Climate resilient energy system • Develop while remaining a low emission economy
Transport	• Freight is dependent on road transport • But road network is limited, and in some areas in poor condition • As urban populations grow, while investment in public transport is limited, traffic congestion is increasing • Roads not climate resilient	• Sustainable, efficient, integrated transport • Freight modal shift from road to rail • Zambia becomes a regional transport hub • Reduced congestion in urban areas • More non-motorised transport • Climate resilient transport infrastructure
Agriculture, forestry and land use	• Maize dominated agriculture, low productivity • Growth has not included small scale farmers • Agriculture and gathering of wood fuel linked to deforestation • Agriculture and fisheries vulnerable to climate	• Sustainable agriculture, forestry and land use, diversified according to agroecological zones • Sustainable forest management – enable contribution to economy while reducing deforestation • Climate resilient agriculture
Economy	• Sporadic economic growth, and high levels of debt, exacerbated by external impacts including COVID-19, Russia-Ukraine war, and drought • Supply chain disruptions exacerbate import dependence, commodity scarcity, inflation • Dependence on foreign finance • Mineral extraction, especially copper is a major economic contributor, but this makes the economy vulnerable to fluctuating global commodity prices • Large informal sector • Regional inequalities	• Diverse, resilient and inclusive economy • Economic diversification, resilient to pandemics • Thriving urban, peri-urban and rural economies • Reduce risks of informal sector • Improved labour productivity, high skilled jobs
Society	• Low access to health care and sanitation • Low education rates • Limited ICT access exacerbates educational inequalities • Education and health disrupted by pandemic • Rural poverty • Gender inequalities • Population growth and urbanisation trends	• Universal and equitable access to health care, education, water and sanitation • Widespread internet access • Improved waste management • More power at local government level to provide services • Pursue development approaches that enhance gender equality • Protect communities against flooding and droughts

biofuel production. Electricity generation increases to meet domestic demand, as well as exporting to neighbouring countries. Public-private partnerships are leveraged to fund road and rail infrastructure in the main transportation corridors.

In the Decentralised scenario, the government pursues devolution of fundamental public service provision, and seeks to promote sustainable small-scale livelihoods within traditional land governance systems. Revenue from mineral extraction is directed to local authorities, and both financial and knowledge transfer is leveraged from international partners to increase domestic skills for value addition in batteries and electromobility. Small-scale climate-smart agriculture techniques are promoted. Small-scale energy hubs and local supply chain coordination support prosperous rural economies, reducing rural–urban migration.

In the following sections we compare in more detail the implications of these two scenarios across the sectors listed in Table 2. Reflecting the mixed-method approach described in Section 4, the descriptions incorporate both qualitative and quantitative material.

5.2.1. Energy

In both scenarios the overall demand for energy increases due to growing populations, growing economic activity, and increased access to energy services. However, a greater general uptake of energy efficiency, as well as investment in infrastructure to support active travel, contributes to a lower overall energy demand in Decentralised (Fig. 2), with resulting lower energy system costs and investment requirements.

Whilst both scenarios retain low CO₂ emissions, at least in comparison to most other countries' per capita emissions in 2024, the CO₂ emissions of Centralised are the higher of the two (Fig. 3), primarily due to the greater reliance on gas and coal in electricity generation.

In both scenarios electricity generation increases rapidly, meeting demands from economic activities and growing electricity access from households. In Centralised, strong growth in mining output further adds to electricity demand. In Decentralised, as the government moves away from ambitious output-driven targets, the mining sector grows at a more moderate pace; and strong energy efficiency regulations further moderate electricity demand growth in commercial and residential sectors. By 2050, total electricity generation in Centralised has increased nine-fold compared to 2015. In Decentralised, electricity generation increases significantly less than in Centralised – but it is still five times the 2015 level by 2050 (Fig. 4).

Different electricity sector policies contribute to a different electricity generation mix (Fig. 4). In both scenarios, competitive auctions allow private power companies to bid for long-term electricity

generation contracts. In Centralised a “flat” network charging regime reduces the incentive for plants to locate close to demand, instead encouraging large scale hydro and gas plants located close to energy supplies. Higher value connections to large urban and industrial centres, and for export to neighbouring countries, are prioritised above lower value connections to sparsely populated rural areas.

In Decentralised, energy subsidies are phased out, moving towards cost-reflective pricing for industrial as well as domestic electricity customers, with the cost impacts mitigated by the uptake of energy efficient technologies, reducing energy consumption and hence overall costs. A locational network charging regime creates incentives for generators to locate closer to demand, which over time increases the spread of generation around the country, reducing the need for transmission investment.

Measures are also taken in Decentralised to enable more diverse participation within decentralised energy production. At the local level, local authorities, local businesses, cooperatives, investors and financial intermediaries coordinate to create small scale renewable energy hubs.

In both scenarios, the electricity generation mix is considerably diversified (Fig. 4). By 2050 both the Centralised and Decentralised scenarios reduce relative dependence on hydro from around 80–90 %, to about 25 % of generated electricity, with wind, solar and bioenergy, and in Centralised, gas, also contributing to the mix. However, in both scenarios electricity generation from hydro still increases in absolute terms. In the Centralised scenario hydro generation in 2050 is 2.5 times the model base year of 2015, or double the level recorded in 2022 (ERB, 2023); in Decentralised the increase is 56 % relative to the base year, or 20 % higher than 2022 levels (Fig. 4).

The high share of variable renewables in the Decentralised electricity mix would require attention to supply–demand balancing. Consequently, significant investments are also made in this scenario in both distributed and grid-scale storage (Fig. 4). Incentives for demand-side response services could additionally contribute to increase system flexibility and reduce costs (Sinsal et al., 2020).

Both scenarios would require substantial infrastructure investments. In Centralised, electricity generation investments average US \$1 billion per year in the 2020s (equivalent to 3 % of GDP in 2022 (World Bank, 2024)), rising to US \$3 billion per year in the 2040s. Electricity generation investments in Decentralised average US \$0.5 billion per year in the 2020s, and rise to around US \$2 billion per year in the 2040s (Fig. 5).

The two scenarios take contrasting approaches on clean cooking. In Centralised, a government clean cooking programme aims to displace woodfuel and charcoal, focussing on electric cooking where the grid is

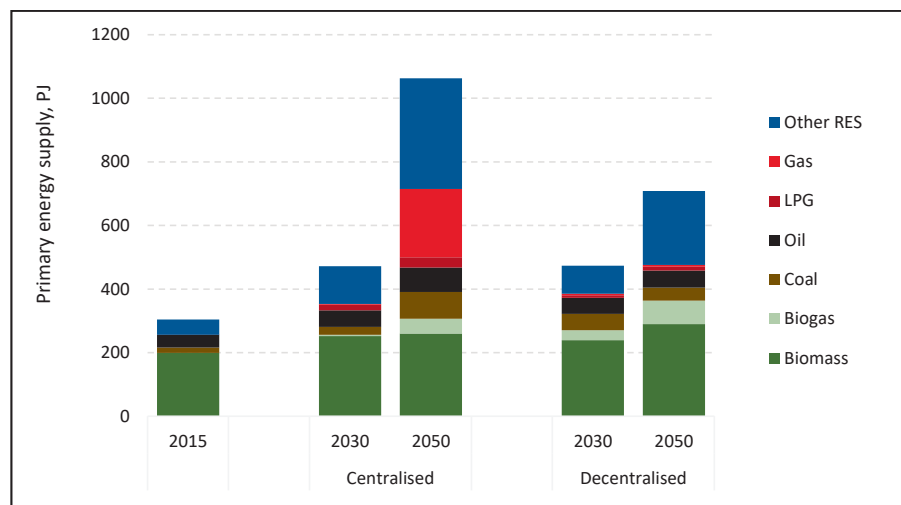


Fig. 2. Centralised and Decentralised scenarios, primary energy supply compared to 2015. Results from OSeMOSYS model. “Other renewables” includes wind, hydro and solar PV, and is based on the physical energy content method for primary energy accounting.

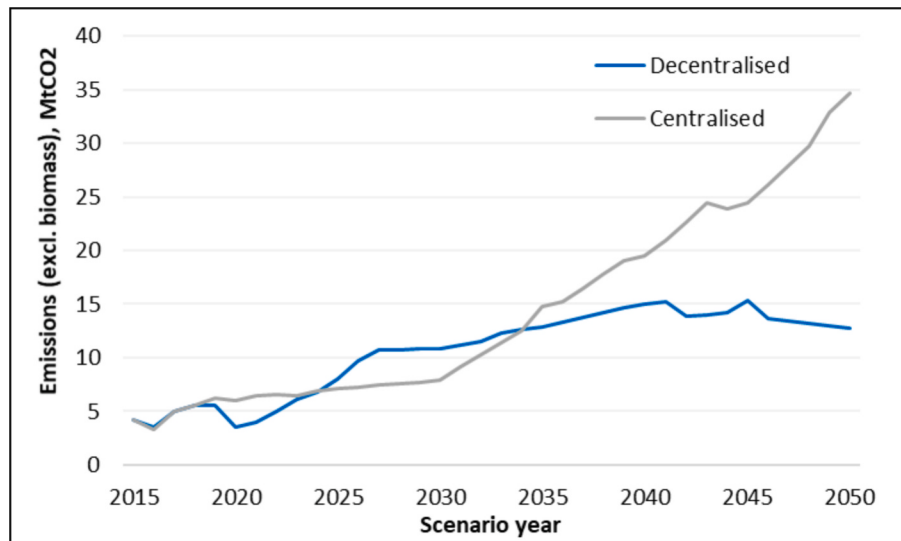


Fig. 3. Centralised and Decentralised scenarios, total energy-related CO₂ emissions. Results from OSeMOSYS model. Figures shown exclude emissions from biomass.

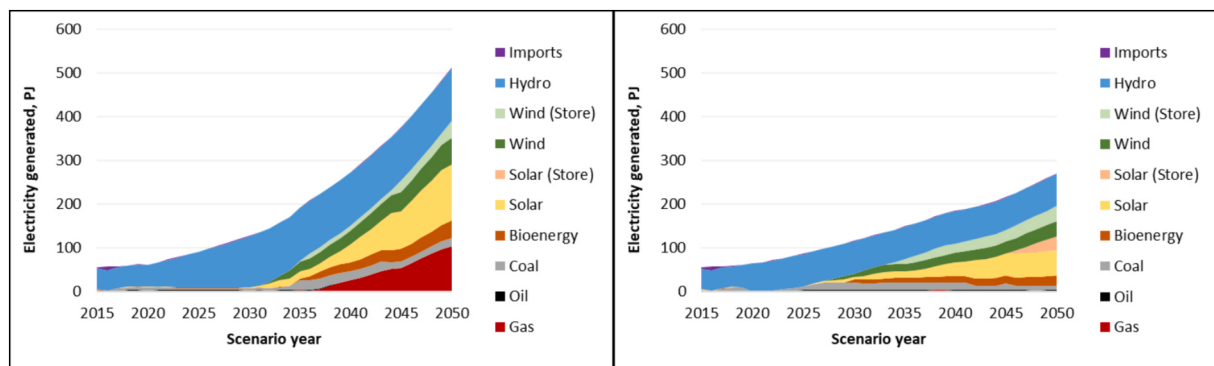


Fig. 4. Centralised scenario (left) and Decentralised scenario (right), electricity production by generation type, 2015–2050, results from OSeMOSYS model.

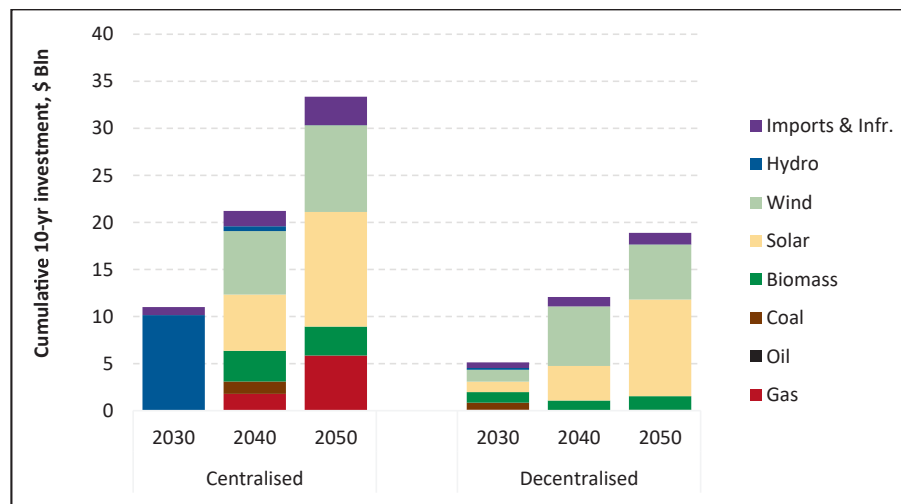


Fig. 5. Centralised and Decentralised scenarios, electricity sector investment, results from OSeMOSYS model. Each year label represents the cumulative investment for the previous ten years.

available, and on LPG stoves in rural areas. By-products of the fermentation processes of biofuel refineries (Section 5.2.3) are used to produce biogas, which provides a clean cooking fuel for rural areas close to the refineries. By 2050, cooking with traditional biomass has been phased

out (Fig. 6).

In Decentralised the clean cooking roll-out takes a region-specific approach, supporting district-level planners to identify appropriate clean cooking solutions based on local characteristics and integration

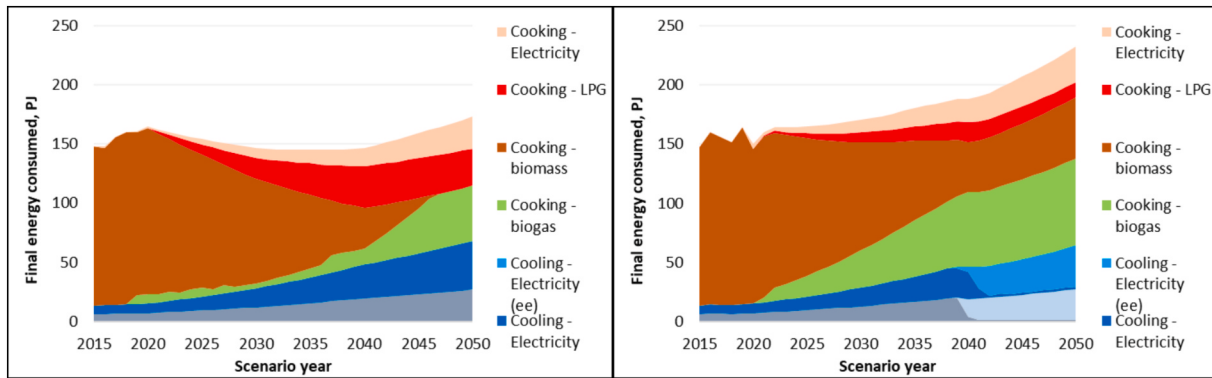


Fig. 6. Centralised scenario (left), and Decentralised scenario (right), household final energy consumption, 2015–2050, results from OSeMOSYS model.

with other economic activities. For example, in some regions agriculture may produce organic by-products that can be used as feedstock for producing biogas at household or community level; in other regions community forestry may yield sustainable renewable wood products which can be used with efficient cookstoves; and in other areas electric or LPG stoves may be most appropriate (Fig. 6).

5.2.2. Transport

In both scenarios transport makes a key contribution to economic activity, but in different ways (Fig. 7). In Centralised, transport is crucial to enabling bulk exports of minerals and agricultural products. Foreign investment is sought to upgrade road and rail infrastructure along key transportation corridors from production areas to international distribution points. Some of the foreign investors are private integrated mining and logistics companies, with an interest in securing the transit of their extracted resources; some are foreign state-owned enterprises, with an interest in securing strategic supply chains. As the government's finances improve, it is able take shares in infrastructure projects as public–private partnerships (PPPs), such as the development of a high-speed passenger rail route between Dar es Salaam and Livingstone, which helps to promote tourism by connecting Mosi-oa-Tunya with a southern African overland circuit. Domestically produced biofuel is blended with imported petrol and diesel, and electric vehicles emerge in urban areas.

In Decentralised, local authorities are increasingly empowered to plan regional transport infrastructure development. Investments focus on connecting the most isolated rural communities to essential services and markets in the closest hub town. In response to concerns about local air pollution in urban areas, regulations are introduced to encourage electric mobility, including micro-mobility. Some of the off-grid renewable energy hubs (Section 5.2.1) also move into electric micro-mobility services, such as rental and charging of e-scooters. These

enterprises act as technology niches to nurture electric vehicle development and manufacturing, which aligns with continued development of battery manufacturing. Local authorities also invest in infrastructure to support active travel (walking and cycling).

Reflecting the very low base of per-capita transport demand, both scenarios see a significant increase in transport energy demand. In Centralised, passenger transport demand has more than tripled by 2050 compared to 2015 (Fig. 7), due to strong GDP growth and greater passenger transportation between large cities, supported by infrastructure investments that also benefit the freight sector.

In Decentralised, 2050 passenger transport energy demand has doubled relative to 2015 levels (Fig. 7). Municipal-scale investments support active travel, which somewhat suppresses the growth in transport energy demand compared to Centralised. Transport infrastructure improvements are evenly distributed around the country, and support a country-wide circuit for both domestic and international tourism. Regions are internally well-integrated with local transport infrastructure.

5.2.3. Agriculture, forestry and land use

In Centralised, the government continues to pursue ambitious targets to increase agricultural production, focussing on facilitating large scale, high-input, export-oriented commercial agriculture. Measures are introduced to expedite the processes of transferring customary land into private leasehold tenure, to encourage private investment. The government partners with the private sector in constructing irrigation infrastructure to supply large-scale agriculture. This requires coordination with plans for hydro power (Section 5.2.1).

There is an increase in production of sugarcane and other crops that can supply both food and biofuel markets, contributing to transportation fuel demand (Section 5.2.2). The government also encourages foreign investments in biofuel refineries, to produce ethanol from sugarcane, and in flex-fuel vehicle manufacturing plants, and incentivises biofuels

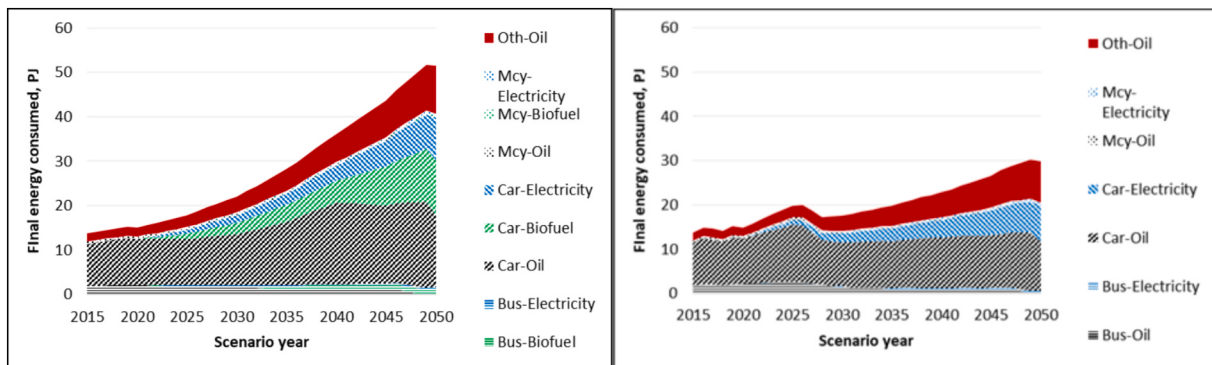


Fig. 7. Centralised scenario (left) and Decentralised scenario (right), passenger transport final energy consumption by mode and fuel, 2015–2050, results from OSeMOSYS model. Mcy = two wheelers; Oth = other, including rail and domestic aviation.

through fuel blending mandates.

In Decentralised, the trend of transferring customary land to private leasehold tenure is much more attenuated than in Centralised. Instead, efforts are made to increase productivity of small-scale farmers, through conservation agriculture approaches that preserve and make efficient use of natural resources. Local agricultural extension agencies also consider appropriate choices and combinations of crops and inputs in their respective regions, taking into account agroecological conditions and climate risks, and integrating traditional knowledge.

Local authorities establish “commodity associations”, which work to understand the competitive advantage of each region, support and develop local markets by connecting farmers with local businesses that can add value, and identify resource synergies in line with circular economy principles. For example, in some areas, agriculture by-products are used to produce biogas and linked in with local energy hubs (Section 5.2.1). Some areas develop community-level forestry management, gaining income from sustainably harvested forest products, or from carbon credits linked to nature-based solutions.

5.2.4. Economy

In Centralised, the mining sector remains key to economic strategy. The government reaffirms ambitious targets to increase mining production, and creates a low-tax enabling environment to encourage foreign private sector investment. Inward investment in a range of mining activities increases, including copper, cobalt, gold, uranium, nickel and manganese. Minerals are mostly exported with minimal value addition taking place in the country. Nonetheless, economic activity in the mining sector gradually trickles down to create opportunities for related service sectors in urban areas, encouraging a continuation in the rural–urban migration trend and an increase in the share of the formal economy.

As well as meeting domestic food demand, agriculture contributes to economic growth through increasing exports. The government’s support for large scale agriculture, and for scaling up mid-scale and emergent farms (Section 5.2.3), result in greater labour productivity, with the result that fewer people are employed in the sector. Thus, services and tourism are crucial for employment, with particular efforts made to promote Livingstone and Mosi-Oa-Tunya to domestic and international visitors.

In Decentralised, a contrasting economic strategy is pursued. The government seeks to diversify the economy away from extractive and export-led processes, and to stimulate local economies to achieve a more distributed pattern of economic activity and value addition. A recalibration of relations with foreign-owned mining companies aims to create stable long-term partnerships with greater fiscal contributions from companies, due to arrangements that reduce opportunities to avoid tax through “profit-shifting.” A mixture of incentives and requirements as part of mining licences ensure that companies invest in socially beneficial infrastructure, domestic value-adding supply chains, and in post-mining remediation of sites.

National Research Institutes are mandated to support knowledge and skills in low carbon sectors consistent with Zambia’s mineral and other resource bases, including alternative battery chemistries, electric vehicles, bioenergy, and climate-smart agriculture. These institutes build links between fundamental research carried out at universities, and the application of that research in industry.

Technologies and skills in batteries and electric mobility are key to the decentralised renewable energy and micromobility hubs that grow up (Sections 5.2.1 and 5.2.2). These small scale renewable energy hubs provide access to distributed energy services at the same time as establishing the value-adding activities and supply chain coordination that enable rising incomes, making the investments financially self-sustaining. As Zambia’s battery manufacturing capability increases, battery storage is integrated within these hubs to increase energy stability. Research in small-scale agriculture techniques is disseminated through local extension services, in support of small-scale farmers

(Section 5.2.3).

As local authorities access more funding to invest in local infrastructure, a whole-Zambia tourist route is becoming established, taking in all the national parks and natural features, and attracting both domestic and international visitors. This growing activity is part of a growing service sector that is evenly spread around the country’s towns and cities.

5.2.5. Society

In Centralised, in spite of low mineral tax rates, mining activity contributes to government revenues, and the tax base increases as the share of formal employment increases, especially in service sectors. In response to a continuing urbanisation trend, the revenues are initially prioritised for urban infrastructure investments, to make cities ready in terms of health, water, sanitation and education. The most rural areas have dwindled in population and lagged in their access to basic services. However, the increasing tax base enables some targeted spending on basic services in rural areas by the end of the scenario period.

In Decentralised, increased rates of fiscal contribution from mineral extraction activities support government revenues. A high share of responsibility for spending is delegated to local authorities, for investments in health, water and sanitation, and education services. As a result of the increasing resilience and prosperity of rural livelihoods the urbanisation trend begins to flatten. Growing prosperity in the regions increases revenue collection at local level, further enhancing the ability of local authorities to invest in local services. Zambia’s largest cities remain moderately sized, while smaller towns and cities have retained their populations.

5.3. How resilient will we be?

The scenarios thus far described focus on how policy and strategy choices of system actors could lead intentionally to alternative outcomes. However, it is also crucial to consider the resilience of these alternative scenarios to future outcomes that cannot be directly controlled by system actors.

A key consideration for any scenario is its resilience to climate impacts, in particular water stress. Both scenarios reduce the *relative* share of hydro in the electricity mix. However, due to overall increasing electricity demands, hydro production increases in absolute terms, doubling in the case of Centralised (Section 5.2.1). These absolute increases could create vulnerabilities in particular hydro-power locations. Vulnerability to drought could be further exacerbated by a water-intensive agriculture sector, which could be a particular risk in the Centralised scenario (Section 5.2.3).

An export-led economic strategy may be subject to market risks, due to fluctuations in the demand for and prices of commodities. One way of mitigating such risks is through a strategy of economic diversification. In Centralised, mining continues to be central to economic growth, but the scenario focusses on diversification within the mining sector, with increased development of a range of minerals. It is hoped that strong activity in mining will also create a “trickle down” effect and indirectly stimulate activity in other sectors including in services. However, there is a risk that this will not lead to broad based development, and regions distant from the mining centres will be left behind. The Decentralised scenario pursues a broader economic diversification strategy by seeking to increase economic activity and value addition, including on agricultural produce, at the local scale (Section 5.2.4, 5.2.5). The aim would be to increase economic resilience by increasing the self-reliance of local economies, and reducing the nation’s dependence on concentrated economic areas based on extraction.

Both scenarios illustrate Zambia’s potential to meet significantly increased energy demands while constraining fossil fuel dependence, through alternative technologies such as renewables, electric vehicles and biofuels, and through demand reduction due to efficiency and active travel (Section 5.2.1, 5.2.2). For a landlocked country without domestic

oil and gas reserves, such a transition could increase resilience against price spikes and supply chain disruptions in international fossil fuel markets.

6. Discussion

As noted in Section 1, climate compatible development is a synergistic model that aims to align climate mitigation and adaptation, with social and economic development (Mitchell and Maxwell, 2010). Climate compatible development should be resilient to external disruptions, and socially inclusive. The comparison of the two scenarios in terms of their consistency with climate compatible development highlights strategic opportunities, as well as risks and challenges. In this section we identify cross-cutting policy and governance recommendations that arise from the consideration of the scenarios, before reflecting on limitations within our process and how these might be improved upon in future research.

6.1. Policy and governance implications

The scenarios emphasise the importance of climate-resilient long-term planning for infrastructure. A significant vulnerability here is Zambia's current reliance on, and possible future expansion of hydro power, which is a feature of both of these scenarios as well as of other recent planning exercises (MOE, 2023). All newly proposed large-scale projects and infrastructure plans should be able to demonstrate long-term climate resilience, against a range of external climate change scenarios, factoring in not only the optimistic or moderate ranges of climate impacts, but more severe outcomes too.

Agriculture is an important sector for Zambia that is also highly vulnerable to climate impacts and water stress (Beck and Bernauer, 2011). Without careful planning, Zambia's ambitions on increasing agricultural production (Hichilema, 2021, p. 12; MoF, 2022) could be in tension with water availability. Consideration must be given of what combination of irrigation and conservation agriculture measures, at large-scale and small-scale, including relatively inexpensive and traditional techniques, and careful crop selection, will most successfully and sustainably reduce the climate exposure of agriculture (Gosnell et al., 2019). Integrated risk assessments, accounting for possible water demands from multiple sectors, including agriculture and energy, will also be critical.

Social and economic development is a key pillar of climate compatible development. As discussed in Section 2, Zambia suffers from high levels of poverty, inequality and low levels of access to fundamental services including health, education and clean energy. Economic growth is essential to raise private and government incomes to enable spending on these critical areas.

However, to be effective, growth must be sustained, rather than sporadic, and resilient to external shocks. The constrained development over the long-term of many low- and middle-income countries is not due to their inability to exhibit fast growth, but rather due to the sporadic nature of that growth, where short periods of fast growth are quickly followed stagnating or negative growth (Andersson, 2018; Broadberry and Gardner, 2022). Zambia is a case in point. Its economy has historically been highly dependent on copper, and this has strongly tied the economic fortunes of the country to the movements of global copper markets, resulting in sporadic economic growth (Dobler and Kesselring, 2019; Mafa and Mathiason, 2022). Copper is considered a critical mineral in the context of the low carbon transition, and hence growing global demand seems probable (IEA, 2022). However, the existence of other significant copper producing countries, and the nature of resource extraction including the delayed feedback effects between exploration, demand and supply, can make commodity prices volatile in the short to medium term, with serious economic impacts especially on highly resource-dependent economies (Roe and Dodd, 2018).

The long-term economic strategy should seek to insulate the

economy from short-term fluctuations in the markets for any particular commodity, and gradually build up the knowledge and skill base of the economy, rather than pursuing targets that are overly influenced by near-term market dynamics. Investments should clearly demonstrate a pathway to creating sustainable economic activity, rather than repeating past mistakes of major infrastructure investments failing to deliver growth and simply contributing to increasing debt (Mbewe et al., 2024). Both scenarios imagine a transformation in the manufacturing capacity and skill base of the Zambian economy, in areas such as biofuels and electric vehicles, with potential for much greater value addition than exporting raw materials. Climate resilient agriculture is also a crucial area in which innovative research could be brought together with traditional knowledge and practices, in order to maintain prosperity in the context of climate risk.

Investments in domestic research capacity, including in National Research Institutes, should be linked to this strategy. A well-known historical example of profound technological transformation is that of South Korea between 1960 and 2020, during which time the country developed successive world-leading industries, while its GDP per capita grew by 30 times in real terms (World Bank, 2024). The cultivation of strategic relationships with potential knowledge transfer partners, and investment in domestic knowledge capacity such as national research institutes, are key lessons from such transitions (Watson et al., 2019).

External partnerships are particularly crucial for countries with limited internal capacity for investment, as is the case for Zambia given its current challenging macro-economic situation (Section 2). However, power imbalances can affect relationships with external partners. There has been longstanding concern about the fairness of the contribution of extractive multi-national enterprises in resource dependent economies (African Union, 2009), and a growing body of macroeconomic evidence that such companies systematically limit their tax contributions through "profit shifting" accounting techniques (Beer and Devlin, 2021; Beer and Loeprick, 2015; Albertin et al., 2021).

The challenge is to establish partnerships that are mutually beneficial, and support Zambia's long-term development priorities, as well as the priorities of the investor. A clear vision and direction of travel for the economy, such as is expressed across these scenarios, would help to articulate these priorities and guide such investments strategically. In demonstrating its ambitions to maintain a low carbon system similar to those represented in these scenarios, Zambia would be able to claim leadership on climate mitigation within the region, which could help to build a case for support from like-minded countries or as part of global climate finance initiatives. Developments such as the EU's Critical Raw Materials Act, which seeks "mutually beneficial partnerships with emerging markets and developing economies", and "like-minded countries willing to strengthen global supply chains" (EC, 2023), could be grounds for optimism about the potential to move from a purely extractivist investment model to one characterised more as a development partnership guided by shared values. Lessons may also be learned from countries such as Norway and Botswana, which have, amongst other things, established sovereign wealth funds for the long-term management of their resource revenues (Qobo and Soko, 2022).

As well as being economically resilient, development must also be inclusive. A risk of a development model based around a large-scale lead sector is that populations distant from such activities are "left behind." The Decentralised scenario's local economic development strategy attempts to raise incomes and generate wealth at local scale, through coordinated regional planning and value chain management, with small-scale energy hubs supporting productive activities and greater local-scale value addition. Partnerships are also essential here, with aggregators and financial intermediaries (AFI, 2020; Anigbogu et al., 2015), including NGOs (COMACO, 2025), potentially playing a crucial role in funnelling investment to small-scale entrepreneurs.

Finally, even though the scenarios are contrasted along a Centralised-Decentralised axis, they both in different ways emphasise the importance of multi-level governance. Centralised would still

require careful local-scale investment planning to ensure that rural areas are not economically left behind. Conversely, it is not sufficient in Decentralised simply to devolve funds to local authorities. Rather, investments must be supported by coordination between governance levels, for example with national research institutes developing knowledge to support extension services at local scales, taking into account regional climatic variations (Waldman et al., 2017), and integrated plans helping to situate local investment priorities within broader regional or national strategies, working with relevant external partners.

6.2. Reflections on the process: limitations, next steps and further research

As described and for the reasons given in Sections 3 and 4, our scenarios approach was participatory, and engaged with mixed qualitative and quantitative methods. However, future scenarios work, in Zambia or in other countries, could nuance or further develop each of these dimensions.

Our participatory approach focussed on engaging with national level policy-makers, representatives of industry and of civil society organisations, because we wanted to develop national scale scenarios with the involvement of national-level decision-makers. However, inclusive and equitable transitions require the consent and participation of wider society. Therefore, future work could use our scenario framework to engage with a wider cross-section of society and at different scales of governance. Building on interest amongst stakeholders at the workshop in whether elements of each scenario could be combined (Appendices C and D), further research could explore the feasibility of “hybrids”, or other variations of the Centralised and Decentralised scenarios.

As explained in Sections 1 and 4, our scenarios took a holistic view of society and the economy, but with a quantitative focus on the energy system as a crucial keystone sector. However, several other elements of the narrative could also have benefitted from quantification, including the wider economy, and implications of the scenarios for agriculture, forestry and other land use. Our reflections on the relative climate resilience of the two scenarios, including in relation to their use of water resources both for electricity generation and agriculture, could in future work be further enhanced by using climate modelling to compare more precisely the exposure to drought risk of each scenario under different global climate change scenarios.

7. Conclusion

This paper has explored the prospects for resilient and inclusive climate compatible development in Zambia. In support of this aim, a novel participatory and mixed-method scenario development process, grounded in theory and practice from scenario literature, was developed, and applied to co-create scenarios with high-level Zambian stakeholders. Analysis and comparison of the scenarios highlighted challenges and opportunities for resilient and inclusive climate compatible development in Zambia, and the following broad policy and governance recommendations:

- Infrastructure investments and long-term economic plans should be tested for both climate and economic resilience. This includes: ensuring that infrastructure and priority economic sectors are resilient to future climate impacts, especially drought, taking into account cross sectoral demands, for example on water resources; pursuing economic diversification within a long term strategy for building domestic capacity, skills and higher value activities; ensuring that investments are conducive to long-term endogenous economic growth, rather than adding to the debt burden
- Pursue mutually beneficial, equitable development partnerships, with like-minded international partners. Use scenarios to help articulate Zambia's ambitions and corresponding needs. Think creatively about how Zambia might benefit from such partnerships,

including not only direct financial investment but also knowledge, skills and technical capacities.

- Appropriately allocate responsibility to different scales of governance – national and regional – and ensure strong coordination, knowledge and information links between them

Every set of scenarios has to be about a particular place. These scenarios were co-created with Zambian stakeholders to explore the future for Zambia; hence the reflections and recommendations they generate are most directly and intentionally relevant to the Zambian context. However, the issues raised by these scenarios will also prompt important questions for decision-makers in other countries, especially those that share some of Zambia's characteristics, for example: a low- or middle-income status; high exposure to climate risk, especially drought; extensive natural resources, but low skill-base and minimal value addition; and ambitions to pursue climate compatible development, encompassing low emissions, high climate resilience and positive development outcomes.

More broadly still, this paper demonstrates that a participatory, mixed-method scenario approach provides a useful framework for national decision-makers, or other groups or communities, to explore climate compatible development. Participatory approaches provide a framework within which stakeholders can explore shared aspirations, become aware of contrasting priorities, but also “find and enlarge the common ground” (Le Roux and Maphai, 1992). Mixed-method approaches combine essential quantitative detail on environmental impacts and limits, and material requirements, within a rich descriptive narrative of social, policy and political priorities. Overall, scenario approaches provide valuable tools for the co-creation of shared sustainable futures.

CRedit authorship contribution statement

Nick Hughes: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mulima Nyambe-Mubanga:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Willard Mapulanga:** Writing – review & editing, Investigation, Formal analysis. **Malonga Hazemba:** Writing – review & editing, Investigation, Formal analysis. **Stephen Chileshe:** Writing – review & editing, Investigation, Formal analysis. **Bernard Tembo:** Writing – review & editing, Investigation, Formal analysis. **Jim Watson:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jen Cronin:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Steve Pye:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Julia Tomei:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Meron Tesfamichael:** Writing – review & editing, Investigation, Formal analysis. **Yacob Mulugetta:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Simon Bawakyillenuo:** Writing – review & editing, Investigation, Funding acquisition, Conceptualization. **Aba Obrumah Crentsil:** Writing – review & editing, Investigation, Formal analysis.

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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Appendices A–E. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloenvcha.2025.103072>.

Data availability

Data will be made available on request.

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