Abstract

Africa has entered a period of rapid population and economic growth that will require a substantial expansion of its power generation capacity in the coming decades. Although the continent has contributed only marginally to historical greenhouse gas emissions, its nations have submitted ambitious climate mitigation pledges which, if coupled with the deployment of Africa's abundant renewable energy resources, could enable the sustainable satisfaction of rising demands. Designing effective energy transition pathways, however, demands careful consideration of Africa's distinctive contextual challenges. Approaches grounded solely in cost minimization risk overlooking the cross-cutting implications of the transition. Moreover, analyses relying exclusively on either global Integrated Assessment Models (IAMs) or continental Energy System Models (ESMs) inherit the methodological limitations of each framework, thereby constraining the robustness of their projections. Building on this context, this thesis develops and applies a set of integrated modelling tools to enhance the design and evaluation of Africa's energy transition strategies, providing policy-relevant and context-sensitive insights.

The first overarching research objective of this thesis is to extend conventional least-cost energy system planning approaches by integrating socio-political and ecological assessments into OSeMOSYS-TEMBA AHA, a continental-scale ESM for Africa. A first sub-objective consists of quantifying the exposure of future cost-optimal cross-border power trades to political instability under alternative socio-economic and climatic scenarios. Results indicate a heightened near-term political risk, particularly under more sustainable scenarios, arising from a temporary increase in power trades among politically unstable countries. A second sub-objective involves the evaluation of the ecological impacts of hydropower expansion strategies on local riverine ecosystems, performed by coupling OSeMOSYS-TEMBA AHA with the water quality model DynQual and the biodiversity impact assessment tool Fishsuit. Findings show that, under low-warming scenarios, targeted dam siting through cost-optimal planning can substantially mitigate ecological impacts. In a high-warming future, by contrast, climate change emerges as the dominant driver of ecosystem risk, thereby limiting the effectiveness of improved siting decisions.

The second broad research objective of this thesis introduces a soft-linking framework that couples GCAM, a global IAM, with OSeMOSYS-TEMBA AHA to enhance the accuracy and policy relevance of power system transition analyses for the African continent. GCAM produces long-term energy demand and emissions trajectories at the global scale, which are then spatially and temporally disaggregated and harmonized for

use within the ESM. This integration yields more spatially explicit and technologically diverse generation portfolios than the IAM alone, particularly under decarbonization scenarios. Furthermore, incorporating the climate pledges submitted by African countries under the Paris Agreement shows that deeper decarbonization can be achieved at only modest additional system cost, contingent upon the mobilization of adequate financial and institutional support.

Together, our findings reveal that uncoordinated or purely cost-driven decarbonization pathways risk amplifying regional instability and environmental degradation, thereby undermining long-term resilience. Moreover, single-model approaches fail to capture the resource diversity and heterogeneous generation potential of African countries. By contrast, the integrated multi-model frameworks developed in this thesis can equip policymakers with tools to anticipate vulnerabilities and design context-tailored energy and climate policies, promoting sustainable development across the continent.