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ARTICLE

A Comparative Assessment of the EMERGE Modelling Toolbox for Mini-Grid Planning in Developing Countries

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ABSTRACT: Mini-grids are increasingly regarded as a key pathway for expanding reliable and low-carbon electricity access in developing countries, but the models used to plan them often differ substantially in scope, temporal resolution, spatial detail, and techno-economic representation. This paper reviews and compares five modelling tools developed within the EMERGE project: Hosting Capacity, Optimal Storage Placement, GREENADVISE, CEPIA, and PowSyBl-METRIX. A generalized techno-economic framework is introduced to provide a common basis for comparison, covering objective functions, decision variables, operational constraints, temporal and spatial resolution, solver structure, economic indicators, and the treatment of renewable variability and local network constraints. The comparison shows that the EMERGE toolbox covers complementary planning layers rather than directly interchangeable optimisation models. GREENADVISE and Optimal Storage Placement capture hourly dispatch and storage dynamics, PowSyBl-METRIX and Hosting Capacity focus on grid-constrained renewable integration, while CEPIA supports long-term national scenario and policy assessment. The results therefore highlight a trade-off between model breadth and operational detail. GREENADVISE supports household and community-level renewable-system optimisation with hourly dispatch and a 20-year financial layer. Optimal Storage Placement and PowSyBl-METRIX explicitly represent network constraints, congestion, curtailment, storage siting, and dispatch decisions. Hosting Capacity evaluates the maximum renewable generation or flexible demand that can be integrated without violating technical limits. CEPIA provides long-term national scenario and policy assessment rather than detailed operational optimisation. The results highlight a persistent trade-off between model breadth and operational detail. Tools with fine temporal and network resolution capture variability, curtailment, flexibility needs, and grid bottlenecks more effectively, whereas national-scale tools better support strategic pathway exploration and policy interpretation. The main contribution of the EMERGE toolbox is therefore not a single universal optimisation model, but an interoperable modelling ecosystem that links household, community, grid-constrained, and national planning perspectives. This multi-scale approach is particularly relevant for African and other developing-country contexts, where grid extension, mini-grids, storage, distributed renewables, and affordability constraints must be assessed jointly.

KEYWORDS: Minigrid; optimisation; energy; modelling; models

1 Introduction

The 21st century presents Africa with both significant challenges and transformative opportunities in the pursuit of socioeconomic development and universal energy access. With the continent's population projected to grow by 1.14 billion people by 2050, ensuring inclusive and equitable development will depend largely on the ability to provide affordable, reliable, and widespread access to electricity [1,2]. Africa's abundant natural resources offer immense potential for clean energy generation; however, unlocking this potential will require coordinated efforts and substantial investments from both public institutions and private stakeholders.

Despite growing efforts to expand renewable energy, Africa's supply remains insufficient to meet projected demand, leaving per capita energy consumption below the global average. A Just Energy Transition is critical, as 600 million people still lack electricity, and 970 million have no access to clean cooking fuels [3,4]. One of the key barriers to effective energy planning is the widespread reliance on models originally designed for industrialised nations, which often fail to reflect Africa's unique socio-economic realities. Currently, around 75% of studies on Africa's energy sector use external modelling frameworks, leading to oversimplified assumptions and inaccurate projections. Traditional models overlook decentralized solutions such as mini-grids and off-grid renewables [5,6]. Recent reviews also highlight that model performance depends strongly on the representation of renewable variability, storage degradation, tariff design, financing conditions, and community-level governance [7].

Other persistent challenges include limited access to high-resolution data, as many energy databases aggregate African nations into broad regions, failing to capture localised conditions. Additionally, energy planning often neglects key household needs, such as clean cooking solutions, which remain a major source of pollution and health risks in many regions. Chronic underinvestment in energy infrastructure further exacerbates the problem—despite hosting 20% of the world's population, Africa attracts less than 3% of global energy investments. These constraints lead to high energy costs, unreliable electricity supply, and scalability issues. Addressing these challenges requires a fundamental shift in energy modelling methodologies, incorporating localised approaches, community engagement, and interdisciplinary frameworks that improve planning and policy outcomes. This need is also supported by recent systematic reviews of energy planning and modelling tools, which show that although energy modelling tools are central to policy formulation and decarbonisation planning, existing tools often fail to fully capture the specific features of Sub-Saharan African countries, including informal economies, regional climate conditions, low electricity access, urbanisation patterns, and political constraints [8].

Recent energy-system modelling studies increasingly emphasise the importance of open-source, transparent, and geographically adaptable tools for energy-transition planning. OSeMOSYS Global provides an open-source and open-data model generator for electricity-system modelling across flexible geographical scopes, while PyPSA-Earth demonstrates how high spatial and temporal resolution, open data, and flexible geographical coverage can support energy-system optimisation in African contexts [9,10]. Together with recent reviews of renewable off-grid mini-grids and energy planning tools in Sub-Saharan Africa [7,8], these studies show that model suitability depends not only on the optimisation algorithm, but also on whether the model captures local data scarcity, renewable variability, storage requirements, financing conditions, tariff design, and community-level demand. Reviews of hybrid renewable mini-grids further show that off-grid electrification studies must jointly consider PV, storage, backup generation, reliability, LCOE, policy support, and community organisation [11].

Against this background, the contribution of this paper is to compare the EMERGE modelling tools through a common techno-economic lens, identifying which tools are appropriate for long-term policy pathways, community-level investment screening, storage siting, hosting-capacity assessment, and network-constrained dispatch. This comparison is particularly relevant for developing-country contexts, where electrification pathways often combine grid extension, isolated mini-grids, storage, distributed renewables, and affordability constraints.

The EMERGE project addresses these gaps by providing an open-source decision-making toolkit tailored to African contexts. The EMERGE Toolbox, an open-source framework, integrates flexible energy modelling, data analysis, and optimisation algorithms tailored to regional contexts, supporting improved renewable energy adoption and efficient energy transitions.

A key component of the EMERGE project is the Common System Architecture (CSA), which ensures the integration of economic, technical, social, and environmental parameters into energy models. The EMERGE project focuses on three diverse case studies, as represented in Fig. 1, ensuring broad replicability across different grid and energy infrastructures.

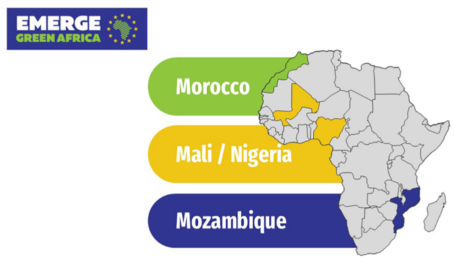

Figure 1: EMERGE map of pilot site.

Fig. 2 provides a conceptual representation of how the five tools interact within the EMERGE modelling ecosystem. CEPIA supports the definition of national and sectoral transition pathways, including policy targets, demand growth, and technology assumptions. These scenario-level assumptions can inform community-scale techno-economic assessment in GREENADVISE, renewable-integration limits in Hosting Capacity, storage siting and sizing in Optimal Storage Placement, and constrained dispatch analysis in PowSyBl-METRIX. The workflow is iterative: results from local and network-constrained tools can feed back into scenario refinement, KPI harmonisation, data-gap identification, and pilot-site calibration.

1.1 North-Western Africa (Morocco)

With a 2024 population of 38.1 million, Morocco is poised to become a regional leader in renewable energy due to its high solar and wind potential. Morocco's GDP per capita reached $4080 [12]. Morocco is strategically positioned to lead North Africa's clean energy transition due to its high solar and wind potential. The country enjoys over 3000 h of sunshine annually, with average solar irradiation around 5 kWh/m^2/day—translating to an estimated technical potential of 500 TWh/year for solar energy. Morocco also has considerable wind energy potential, with studies indicating a capacity of nearly 25 GW. These resources provide a strong foundation for Morocco's clean energy transition. Despite its renewable potential, Morocco remains reliant on imported fossil fuels, which currently constitute approximately 68% of its installed energy capacity. The remaining 32% is generated from renewable sources such as hydropower, wind, and solar [13]. Nevertheless, Morocco has emerged as one of North Africa's frontrunners in renewable energy development, increasing its renewable share from 6% in 2000 to 19% in 2020. As of 2019, Morocco accounted for roughly half of North Africa's renewable electricity generation. The country came close to meeting its target of 42% renewable capacity by 2020, achieving 37% despite institutional and pandemic-related constraints [14]. The energy consumption profile is dominated by the building sector (36%), followed by transportation (35%), industry (19%), and agriculture (8%) [14]. These figures underscore the need for targeted interventions across multiple sectors to improve energy efficiency and reduce carbon intensity.

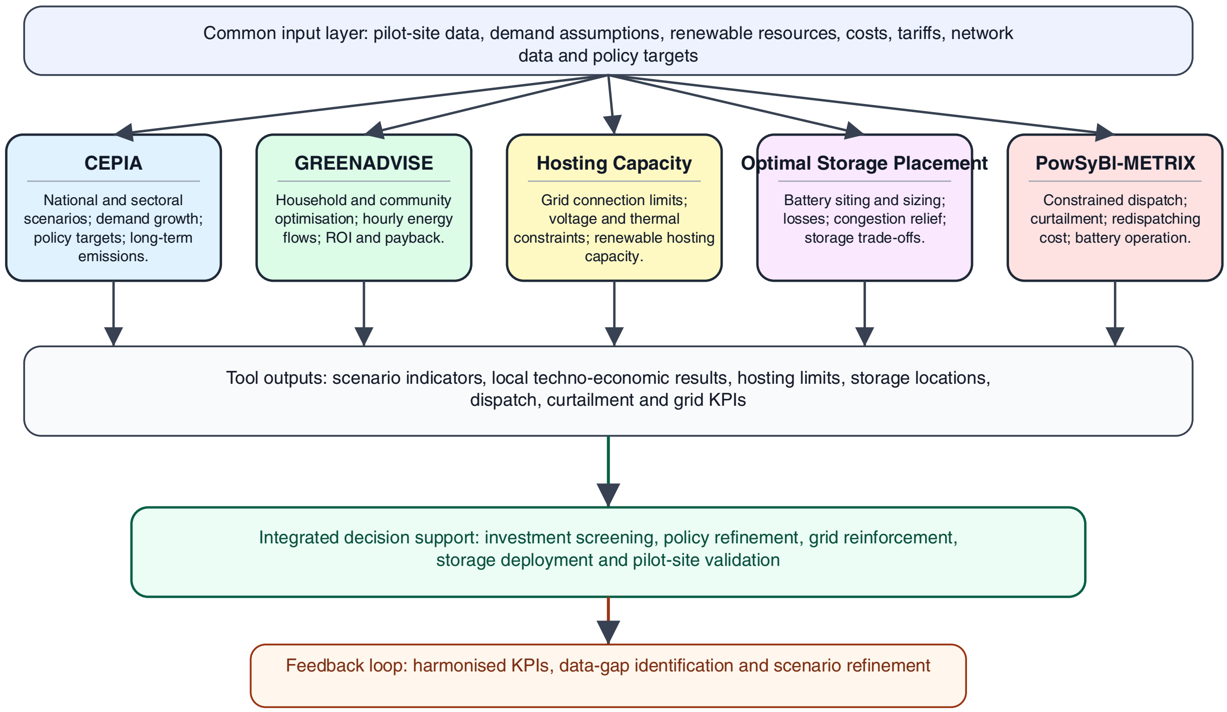

Figure 2: EMERGE toolbox integration workflow.

1.2 East Africa (Mozambique)

Mozambique is located in the Southern Hemisphere, along the southeast coast of the African continent. As of 2024, Mozambique has a population of 34.6 million, with 59% residing in rural areas and a population density of 44 people per km^2. Mozambique's GDP is $22.98 billion, with a per capita income of $659.1—among the lowest in Sub-Saharan Africa [15]. Mozambique is endowed with abundant renewable energy resources. Solar energy potential is particularly high, with irradiation levels ranging between 1785 and 2206 kWh/m^2/year in regions such as Cabo Delgado, Nampula, Tete, and Niassa—where Tete's conditions approach global benchmarks. The country also possesses substantial hydropower potential across 13 major river basins, which currently supply 99% of its renewable electricity. However, this heavy reliance on hydropower renders the system vulnerable to the impacts of climate variability. Wind energy holds considerable promise, especially in coastal regions like Ponta de Ouro and Mavelane, with average wind speeds between 6–8 m/s, though this potential remains largely untapped. Biomass remains the most consumed energy source, accounting for nearly 80% of total energy use—primarily for cooking and industrial processes. Estimates suggest that Mozambique could generate over 2 GW of electricity from biomass-based sources. Mozambique's energy sector is characterised by a high dependence on biomass and underdeveloped grid infrastructure. Despite the country's vast renewable potential, electrification remains limited, particularly in rural areas. The electrification rate has improved from just 5% in 2001 to 44% in 2022 [16]. However, this progress is uneven: while 79.4% of urban residents had access to electricity in 2022, only 5% of rural inhabitants—where the majority of the population lives—enjoyed the same. This stands well below the global average rural access rate of 84%. The national grid reaches approximately 30% of the population. Many district capitals and remote regions depend on diesel generators, which are expensive, inefficient, and environmentally damaging. Mozambique's electricity generation capacity was 2.8 GW in 2023, with 80% derived from renewable sources. Hydropower dominates the energy mix (79%), followed by a marginal share from solar PV (1%) and other renewable sources. While Mozambique performs well in renewable penetration, the energy supply is still inadequate in meeting national demand, particularly for rural and peri-urban areas.

1.3 Niger River Region (Mali/Nigeria)

The Niger River, spanning over 4100 km and draining an area of approximately 2.1 million km^2, is a vital socio-economic artery in West Africa. Originating in the Guinea Highlands and traversing countries such as Mali, Niger, and Nigeria before reaching the Atlantic Ocean, the river supports key sectors including agriculture, transportation, and energy. In particular, its hydropower potential has played a central role in shaping energy strategies in Mali and Nigeria, where several large dams have been constructed along its course. The river basin also holds significant petroleum reserves, particularly in Nigeria, making it a focal point for integrated energy and environmental planning.

Mali, West Africa's second-largest country by land area (1.24 million km^2), is home to an estimated population of 24.5 million (2024), with a low population density of around 20 people/km^2. The country faces considerable geographic and environmental challenges, including frequent droughts, advancing desertification, and limited infrastructure. With a GDP per capita of $900, Mali's economy is predominantly agrarian, and energy access remains a barrier to economic development. The energy sector in Mali is underdeveloped, with access disparities between urban (59%) and rural (14%) populations. Total installed capacity stood at 0.94 GW in 2021, of which only 21.2% was derived from renewable sources—primarily hydropower, contributing around 92% of the renewable share [17]. The remaining energy mix includes biofuels and a small but growing presence of solar and wind energy. Mini-grids have emerged as a promising solution for rural electrification, with over 150 systems currently in operation. However, many of these rely on diesel generators, which are expensive and environmentally unsustainable. Mali's rural energy agency, AMADER, plays a key role in subsidising access and promoting clean alternatives in off-grid areas [18].

Nigeria, the most populous country in Africa with over 232 million people (2024) and a population density of 255 people/km^2, is one of the continent's largest economies. With a GDP of $252.74 billion and a GDP per capita of $1110, Nigeria holds vast energy resources, both fossil and renewable. Yet, despite its size and economic weight, the country struggles to meet the energy demands of its population. Nigeria's installed capacity was approximately 13.25 GW in 2021, with renewable energy contributing just 11.2%, mainly through hydropower. The remainder is dominated by gas-fired power plants. Electricity access remains uneven—while 89.2% of urban residents have access, the figure drops to less than 23% in rural areas [19]. Nigeria has one of the highest solar irradiation rates in Africa, averaging 5535 kWh/m^2/year, and has an exploitable hydropower potential exceeding 14 GW. Despite these advantages, infrastructure, financing, and governance remain critical bottlenecks [18]. Through the integration of localised data, modular modelling approaches, and a focus on decentralised energy solutions, the EMERGE project aims to provide a more effective, scalable, and inclusive energy transition framework for Africa.

The three regional contexts show that renewable resource potential must be interpreted together with temporal variability, demand distribution, and network constraints. Solar and wind resources require models able to represent hourly or sub-hourly intermittency, while hydropower-dominated systems must consider climate variability, seasonal inflows, and resilience to drought. In sparsely populated rural areas, load dispersion and limited grid capacity make the choice between grid extension, mini-grids, stand-alone systems, and storage highly location-specific. Therefore, the selection of an optimisation model cannot be based only on the availability of renewable resources; it must also reflect whether the model can capture local resource profiles, weak-grid constraints, curtailment risks, affordability, and long-term policy objectives.

2 Methods

The CSA developed within the EMERGE project was developed through a comprehensive methodology, starting with a review of open-source energy models. This review aimed to identify the most relevant features present in the EMERGE Toolbox as detailed in Tables 1 and 2 below. The core objective was to examine the models' features, goals, strengths, and limitations to uncover recurring patterns and potential synergies that could strengthen the application of energy modelling tools in Africa's energy transition.

Table 1: Comparison of EMERGE modelling tools: planning scope and modelling structure.

Tool	Main Planning Scale	Temporal Resolution/Horizon	Optimisation or Modelling Class
CEPIA	National/sectoral scenario planning	Five-year steps up to 2050/2055	Scenario and impact assessment; bottom-up sectoral modelling
Hosting Capacity	Distribution/transmission grid nodes	Scenario/time-series based grid assessment	Power-flow-based hosting capacity assessment
Optimal Storage Placement	Network-constrained storage planning	Hourly operation within planning scenarios	Hierarchical/bi-level optimisation; GA or NSGA-II at planning level and OPF or LP/NLP at operational level
GREENADVISE	Household, prosumer, community, small city	Hourly simulation over one year; 20-year financial layer	Linear optimisation
PowSyBl-METRIX	Transmission/network operation	Hourly time series; demonstrated on 24-h scenarios	Network-constrained OPF and iterative battery dispatch simulation

Table 2: Comparison of EMERGE modelling tools: constraints, solvers, economics and resource representation.

Tool	Main Constraints	Solver/Engine
CEPIA	Sectoral demand assumptions; technology adoption pathways; fuel and energy-balance assumptions	Excel-based calculation framework
Hosting Capacity	Voltage limits; line/transformer loading; convergence limits; losses	Load-flow/power-flow routines

(Continued)

Table 2 (continued)

Tool	Main Constraints	Solver/Engine
Optimal Storage Placement	SOC dynamics; charge/discharge limits; PTDF or power-flow constraints; thermal limits; voltage/security constraints	Genetic algorithm/NSGA-II coupled with DC-OPF, LP/NLP or power-flow evaluation
GREENADVISE	Energy balance; renewable allocation; battery and buffer storage dynamics; charge/discharge limits; grid exchange limits; heat-pump coupling	Python/Pyomo with CBC solver
PowSyBl-METRIX	Line ratings; network topology; generation-demand balance; battery energy and power limits	PowSyBl-METRIX; OPF mode with Python binding

The tools should therefore not be interpreted as producing directly comparable outputs for the same decision problem. Instead, they operate at different planning scales and temporal resolutions. CEPIA provides long-term national and sectoral scenario analysis using coarse time steps, while GREENADVISE, Optimal Storage Placement, Hosting Capacity, and PowSyBl-METRIX provide finer operational or network-oriented representations. This distinction is essential when interpreting the results, because only the hourly and network-constrained tools can explicitly represent short-term variability, storage operation, curtailment, congestion, and local technical constraints. Overall, GREENADVISE is best suited for household/community techno-economic screening, Optimal Storage Placement for network-constrained storage design, Hosting Capacity and PowSyBl-METRIX for renewable integration and congestion assessment, and CEPIA for long-term national scenario exploration.

Socioeconomic and environmental factors, such as informal economies, rural-urban disparities, and climate vulnerability, were central to evaluating how well existing models capture local realities. Many existing models, originally developed for industrialised contexts, lack the flexibility to address the region-specific needs of African countries, particularly in handling disaggregated data, cross-sectoral interactions, and decentralised energy systems.

The identification of shared data formats, simulation practices, and scenario design techniques provided valuable insights for enhancing interoperability and optimising model integration in Africa's energy planning landscape.

The treatment of renewable variability differs significantly across the tools. GREENADVISE directly uses hourly renewable production data, whether obtained from external databases, physical models, or user-uploaded measurements, and therefore captures local intermittency in dispatch and storage decisions. Optimal Storage Placement, Hosting Capacity, and PowSyBl-METRIX incorporate variability indirectly through time-series network loading, congestion, curtailment, and flexibility requirements, which is particularly relevant when renewable siting decisions interact with transfer limits. By contrast, CEPIA represents renewable deployment through coarser exogenous scenarios and therefore supports strategic pathway analysis rather than operational mini-grid design.

2.1 Practical Data Requirements and Data Scarcity Challenges

Practical application of the EMERGE toolbox depends strongly on the availability, resolution, and consistency of input data. This issue is particularly important in developing-country contexts, where energy data are often incomplete, aggregated at national level, inconsistent across sources, or unavailable at hourly and network-node resolution. The five tools therefore have different data requirements and different levels of sensitivity to data scarcity, as show in Table 3.

Table 3: Data requirements for EMERGE toolbox models.

Tool	Minimum Data Requirements	Main Data-Scarcity Challenge	Practical Mitigation
CEPIA	Population, sectoral demand, installed capacity, technology shares, fuel prices, emission factors, policy assumptions	National data may be aggregated or inconsistent across sectors	Use transparent assumptions and sensitivity analysis
GREENADVISE	Local demand, renewable profiles, tariffs, technology costs, storage parameters, CO_2 factors	Hourly demand and renewable profiles may be unavailable	Use simulated/interpolated profiles and report uncertainty
Hosting Capacity	Grid topology, bus/branch data, voltage limits, load/generation profiles	Distribution-network data may be incomplete	Use simplified screening first, then AC validation
Optimal Storage Placement	Network model, candidate BESS buses, battery costs and limits, dispatch profiles	Storage value depends on uncertain profiles and costs	Use scenario analysis and Pareto trade-offs
PowSyBl-METRIX	Network topology, line ratings, hourly dispatch data, battery data, redispatch assumptions	Market and dispatch assumptions may not be calibrated	Present results as scenario-based operational indicators

CEPIA requires national and sectoral data, including population, electrification rates, sectoral energy demand, technology shares, fuel use, energy prices, installed capacities, emission factors, and policy or technology-adoption assumptions. Because CEPIA operates at five-year time steps, it can be applied even when hourly operational data are not available, but its results depend strongly on the quality of long-term assumptions.

GREENADVISE requires local demand data, renewable-resource profiles, technology costs, storage parameters, electricity tariffs, buy-back prices, emission factors, and user-defined assumptions on renewable and storage technologies. When measured hourly data are unavailable, the tool can rely on simulated or interpolated profiles, but uncertainty in demand and renewable generation directly affects self-consumption, grid exchange, payback time, and CO_2-saving estimates.

Hosting Capacity requires grid-topology data, bus and branch parameters, transformer ratings, voltage limits, load and generation profiles, and operational constraints. Its applicability is therefore strongly affected by the availability of reliable distribution or transmission network data. In data-scarce systems, simplified or linearised power-flow assumptions may be useful for preliminary screening, but full AC validation remains necessary for investment-grade grid studies.

Optimal Storage Placement requires network data, candidate BESS locations, battery power and energy capacity limits, state-of-charge constraints, load and generation profiles, cost assumptions, and dispatch or price signals. The quality of storage siting results depends on the consistency between operational profiles, network constraints, and economic assumptions.

PowSyBl-METRIX requires network topology, line ratings, generation and demand time series, battery parameters, redispatching assumptions, and operational constraints. It is therefore most appropriate when sufficient grid and dispatch data are available to represent congestion, curtailment, and flexibility operation. Where such data are incomplete, results should be interpreted as scenario-based technical insights rather than calibrated market outcomes.

Overall, data scarcity does not affect all tools in the same way. Scenario-oriented tools such as CEPIA can support strategic planning under limited data availability, while GREENADVISE and the grid-oriented tools require progressively higher temporal, spatial, and technical detail. This reinforces the value of a modular toolbox: different tools can be used according to the maturity of available data, and their outputs can help identify which additional data are most important for future validation.

2.2 Generalized Techno-Economic Optimisation Framework for Mini-Grid Planning

To provide a common analytical basis for comparing the EMERGE tools, the reviewed models can be interpreted through a generalized techno-economic planning problem. In its compact form, the planner seeks a set of investment, dispatch, storage, grid-exchange, and reliability decisions that minimise total system cost while accounting for renewable variability, unmet demand, emissions, and network constraints:

$$\min C_{tot} = \sum_i \left(a_i CAPEX_i K_i + FOM_i K_i \right) + \sum_t \Delta t \left[\sum_i c_{i,t} P_{i,t} + c_{imp} P_{imp,t} - c_{exp} P_{exp,t} + VOLL U_t + c_{\mathrm{CO2}} E_t \right]$$

subject to:

$$\sum_i P_{i,t} + P_{dis,t} + P_{imp,t} + U_t = \Delta \mathrm{t} + P_{ch,t} + P_{exp,t} \forall \mathrm{t}$$

$$0 \le \mathrm{PRE}, t \le \mathrm{KRE\ CFRE}, t \forall t$$
$$SOCt = SOCt - 1 + \eta chPch, t\Delta t - Pdis, t\Delta t / \eta dis \forall t$$
$$0 \le SOCt \le \mathrm{KBESS}, 0 \le \mathrm{Pch}, t \le \mathrm{Pch, max}, 0 \le \mathrm{Pdis}, t \le \mathrm{Pdis, max} \forall t$$
$$\mathrm{Sij}, t \le \mathrm{Sij, max},\ \mathrm{Vmin} \le \mathrm{Vn}, t \le \mathrm{Vmax} \forall i, j, n, t, \text{where network constraints are represented.}$$

here, K_i denotes installed capacity, $P_{i,t}$ generation or conversion output, $P_{ch,t}$ and $P_{dis,t}$ battery charge and discharge power, *SOCt* the state of charge, $P_{imp,t}$ and $P_{exp,t}$ grid imports and exports, U_t unmet demand or reliability slack, CFRE,t renewable availability, E_t emissions, and *VOLL* the value of lost load. Depending on the tool, this general structure may be implemented as linear programming, optimal power flow, metaheuristic optimisation, iterative simulation, or scenario-based assessment.

The unmet-demand variable is particularly relevant for fully islanded mini-grids, where reliability depends on the real-time balance between renewable generation, storage, controllable backup generation, and demand. In operational mini-grid models, this term may be interpreted as loss of load, energy not served, or reliability slack. In contrast, long-term scenario tools may represent reliability only indirectly or through aggregate assumptions.

For fully islanded mini-grids, the unmet-demand term should be interpreted through operational reliability indicators that are more specific than aggregate energy balance. The most relevant indicators include Energy Not Served (ENS), defined as the total electricity demand that cannot be supplied over the simulation horizon; Loss of Load Probability (LOLP) or Loss of Power Supply Probability (LPSP), which measure the frequency or probability of supply failure; unmet-demand hours, which count the number of time steps in which demand is not fully served; and autonomy hours, which indicate how long the system can supply demand using storage or backup generation without renewable input. These indicators are particularly important for PV-battery-diesel or PV-battery-backup systems, where reliability depends on hourly renewable variability, battery state of charge, backup-generator availability, and the economic penalty assigned to unserved demand. By contrast, grid-oriented tools mainly evaluate operational security through voltage violations, line loading, transformer loading, congestion, losses, and curtailment.

2.3 Hosting Capacity, Developed by CIRCE

The Hosting Capacity tool evaluates the maximum additional renewable generation or flexible demand that can be connected to a given grid without violating operational limits. In generic optimisation terms, the tool seeks to maximise admissible connection capacity subject to power-flow feasibility, branch thermal limits, transformer loading, voltage-security constraints, and convergence criteria. Within EMERGE, this function is particularly relevant for weak-grid and grid-edge contexts, where renewable resource abundance may be constrained by local transfer capacity. The tool therefore links renewable integration potential to concrete grid bottlenecks, identifying where new generation can be connected directly and where flexibility, storage, or reinforcement may be required to avoid curtailment. This approach is consistent with recent hosting-capacity literature, where the maximum admissible PV penetration is assessed by comparing deterministic and stochastic methods under distribution-network operating constraints, thereby providing network planners with quantitative insight into the capability of feeders to accommodate new renewable generation [20].

The Hosting Capacity tool is therefore most relevant for weak-grid, grid-edge, and distribution/transmission-constrained contexts where renewable integration is limited by voltage, thermal loading, transformer capacity, or convergence constraints. It is less suited, on its own, to fully islanded mini-grid design, where the dominant constraints are often hourly energy balance, storage autonomy, backup generation, and loss-of-load probability.

2.4 Optimal Storage Placement, Developed by CIRCE

Optimal Storage Placement is a hierarchical multi-objective framework for siting and sizing battery energy storage systems under network constraints. At the planning level, the algorithm explores candidate BESS configurations, including installation bus, rated power, and energy capacity. At the operational level, the model determines the charge-discharge schedule subject to state-of-charge dynamics, power limits, line-flow constraints, voltage or security constraints, and generation-demand balance. The tool can therefore expose trade-offs between economic performance, such as arbitrage revenue or net present value, and technical performance, such as loss reduction, congestion relief, and voltage improvement. This makes it suitable for identifying storage investments that provide both local and system-wide benefits.

In optimisation terms, the Optimal Storage Placement tool can be interpreted as a hierarchical planning-dispatch model. The upper level selects the BESS location, rated power, and energy capacity, while the lower level computes the hourly charge-discharge schedule subject to state-of-charge dynamics, power limits, and network constraints. This structure produces a set of non-dominated solutions rather than a single optimum, allowing planners to observe the trade-off between economic value and technical grid performance.

2.5 GREENADVISE, Developed by UNIZAG

GREENADVISE is a Python/Pyomo-based linear optimisation tool for household, prosumer, and community-scale renewable energy systems. The model operates at hourly resolution over 8760 time steps and allocates local renewable generation among direct electricity use, thermal demand through heat-pump coupling, battery charging, buffer storage, grid export, and curtailment. The optimisation is constrained by electricity and thermal energy balances, renewable generation availability, storage state-of-energy dynamics, charging and discharging limits, grid exchange limits, and user-defined technology parameters. In addition to operational optimisation, GREENADVISE includes a 20-year financial layer that reports investment cost, operating cost, revenues, savings, return on investment, payback time, and CO_2-related indicators. It is therefore best suited to techno-economic screening of renewable solutions at household and community scale. This distinction is relevant because recent work on grid-optimal energy community planning shows that considering network constraints during community design can enable high PV penetration while avoiding critical grid-stability issues, with only limited reduction in community-level benefits compared with purely cost-optimal planning [21].

2.6 CEPIA, Developed by Artelys

CEPIA is not a detailed operational mini-grid optimiser, but a long-term scenario and impact assessment tool. It evaluates user-defined policy and technology levers across the residential, transport, industry, agriculture, and energy-supply sectors through a bottom-up calculation structure. Its main outputs are long-term economic, energy, and environmental indicators, which support policy interpretation and strategic pathway comparison. CEPIA is therefore valuable for analysing national transition scenarios, sectoral decarbonisation options, and policy implications, while its main limitation for mini-grid design is the absence of detailed hourly dispatch, storage operation, and network-level constraints.

CEPIA is not intended to perform detailed operational mini-grid optimisation. Its five-year scenario structure is suitable for policy and sectoral pathway analysis, but it does not capture hourly or sub-hourly intermittency, storage cycling, backup-generator dispatch, loss-of-load events, or real-time balancing between PV, batteries, and demand. For this reason, CEPIA should be used to define long-term policy trajectories and sectoral assumptions, while operational mini-grid sizing and reliability assessment should be carried out using tools with hourly dispatch, storage dynamics, and reliability constraints.

2.7 PowSyBl-METRIX, Developed by Artelys

PowSyBl-METRIX is a network-oriented modelling framework for analysing constrained power-system operation. In the EMERGE context, it uses hourly time series of generation and demand together with network topology, line ratings, and battery parameters to compute feasible dispatch plans under grid constraints. Through its OPF mode and iterative battery-dispatch procedure, the tool minimises redispatching costs and renewable curtailment while respecting electrotechnical constraints. It is therefore particularly relevant for assessing how storage and other flexibility resources can increase the effective hosting capacity of renewable generation in constrained grids.

The results show that storage integration reduces both renewable curtailment and redispatching cost in the tested network-constrained case. Moving from no battery to two batteries decreases curtailment from 2.04 to 1.33 GWh, corresponding to a 34.8% reduction. Redispatching cost decreases from 4.47 to 1.76 million EUR, corresponding to a 60.6% reduction. Although these values are based on preliminary test-case inputs and should not be interpreted as calibrated market results, they demonstrate the type of quantitative insight that network-constrained tools can provide.

PowSyBl-METRIX is particularly appropriate when the mini-grid or local energy system is embedded in, or coupled to, a constrained network. In fully islanded systems without meaningful network interconnection, its grid-congestion focus should be complemented by models that explicitly represent autonomous PV-battery-diesel balancing, reliability constraints, and affordability metrics.

3 Results

3.1 Quantitative Comparison and Representative Model Outputs

Tables 1 and 2 show that the EMERGE tools differ not only in spatial scale but also in temporal resolution, optimisation class, and KPI coverage. CEPIA operates at five-year steps up to 2050/2055 and is therefore most suitable for national policy pathway exploration. By contrast, GREENADVISE, Hosting Capacity, Optimal Storage Placement, and PowSyBl-METRIX operate at hourly or network-operational resolution and can represent short-term variability, storage behaviour, congestion, and curtailment more explicitly. This difference in temporal granularity strongly affects which trade-offs are analysed endogenously: national scenario tools capture long-term sectoral transitions, whereas grid and community tools capture operational feasibility and local bottlenecks.

A representative example is provided by the PowSyBl-METRIX demonstration on the Mozambique network model. In a 24-h test case, three configurations were compared: no battery, one battery, and two batteries. The integration and optimisation of batteries reduced renewable curtailment from 2.04 GWh in the base case to 1.70 GWh with one battery and 1.33 GWh with two batteries, corresponding to an approximate 35% curtailment reduction. Redispatching costs decreased from 4,474,492 EUR in the base case to 2,283,010 EUR with one battery and 1,762,955 EUR with two batteries. These cost values should be interpreted only as test-case indicators, because the input generation and demand values used in the preliminary demonstration were not yet calibrated to realistic market conditions. Nevertheless, the example illustrates the type of quantitative planning insight that network-constrained tools can provide: storage does not only shift energy over time, but also reduces curtailment and relieves grid constraints.

A second representative example is provided by the Optimal Storage Placement framework. The tool evaluates candidate BESS configurations defined by installation node, rated power, and energy capacity. For each candidate design, the operational layer computes the charge-discharge profile under network constraints, while the planning layer compares non-dominated solutions. This produces a Pareto-type interpretation of storage planning, where higher economic value, such as arbitrage revenue or net present value, must be assessed against technical indicators such as active-power losses, congestion relief, voltage improvement, and renewable utilisation. This structure is particularly relevant for African grids, where investment resources are limited and storage should be located where it provides both local and system-wide benefits.

A complementary example is provided by GREENADVISE, which produces quantitative outputs at household, prosumer, or community scale. Unlike PowSyBl-METRIX, which focuses on network-constrained dispatch and redispatching costs, GREENADVISE evaluates local renewable-energy configurations through hourly energy-flow optimisation over one year and a financial assessment over a 20-year horizon. Its outputs include hourly renewable generation allocation, direct self-consumption, grid import, grid export, battery charging and discharging, curtailment, investment cost, operating cost, revenues, savings, return on investment, payback time, and CO_2-related indicators. In this way, GREENADVISE provides quantitative evidence on whether a local renewable configuration is financially and environmentally attractive for households, prosumers, or communities.

CEPIA provides a complementary type of quantitative output at national and sectoral scale. Rather than simulating hourly dispatch, CEPIA compares long-term policy scenarios through indicators such as sectoral final energy consumption, electricity generation by technology, greenhouse-gas emissions, investment costs, operating costs, and renewable-energy penetration. Within the EMERGE demonstrations, CEPIA has been used to explore scenarios aimed at reducing national greenhouse-gas emissions by at least 40% by 2055. These outputs are not directly comparable with hourly dispatch indicators, but they are useful for defining policy pathways and assumptions that can subsequently inform more detailed local or grid-constrained analyses.

3.2 Trade-Offs between Cost, Reliability, and Environmental Performance

A meaningful comparison of mini-grid and grid-edge planning tools requires a common set of performance indicators. In this study, the most relevant KPIs are annualised cost or total system cost, unmet demand or reliability penalty, renewable share, renewable curtailment, CO_2 emissions or CO_2 savings, grid import dependence, and network-security indicators such as voltage violations, line loading, and losses. These KPIs are not represented uniformly across the EMERGE toolbox. GREENADVISE directly combines operational costs with financial indicators such as ROI and payback time. Optimal Storage Placement exposes trade-offs between investment cost, arbitrage value, network losses, and congestion relief. Hosting Capacity and PowSyBl-METRIX emphasise technical feasibility, renewable absorption, congestion, and curtailment. CEPIA provides broader environmental, economic, and socio-economic indicators at national scale.

The comparison therefore shows that no single tool dominates all dimensions of the cost-reliability-environment trade-off. Instead, each tool resolves a different part of the planning problem. For household or community-level decisions, GREENADVISE offers the most direct link between renewable self-consumption, financial performance, and emissions. For grid-constrained renewable integration, Hosting Capacity and PowSyBl-METRIX provide stronger representation of technical limits and curtailment. For storage investment decisions, Optimal Storage Placement provides a more explicit multi-objective perspective. For national policy pathways, CEPIA offers broader sectoral and long-term scenario interpretation.

To improve comparability across tools, future applications of the EMERGE toolbox should report a minimum common set of techno-economic KPIs. These should include net present cost, levelised cost of electricity, annualised capital and operating cost, cost of unmet demand, renewable curtailment cost, CO_2 emissions or avoided emissions, and reliability indicators such as energy not served. These indicators would not eliminate methodological differences among the tools, but they would provide a common interpretation layer for comparing planning outcomes.

To make this comparison more explicit, Tables 4 and 5 maps the main techno-economic, reliability, environmental, and grid-security KPIs against the five EMERGE tools. The table distinguishes between KPIs that are directly calculated by the tool, indicators that can be derived from available outputs, indicators that are only partially represented, and indicators that are outside the intended modelling scope. This matrix does not imply that all tools should produce identical outputs; rather, it provides a common interpretation layer for understanding how each tool contributes to mini-grid and grid-edge planning.

Table 4: Representative quantitative outputs from the PowSyBl-METRIX Mozambique 24-h demonstration.

Configuration	Curtailment [GWh]	Curtailment Reduction vs. Base	Redispatching Cost [EUR]	Redispatching Cost Reduction vs. Base
No battery	2.04	–	4,474,492	–
One battery	1.70	16.7%	2,283,010	49.0%
Two batteries	1.33	34.8%	1,762,955	60.6%

Table 5: KPI/indicator comparison between EMERGE models toolbox.

KPI/Indicator	CEPIA	GREENADVISE	Hosting Capacity	Optimal Storage Placement	PowSyBl-METRIX
Total system cost/annualised cost	Partial/scenario-level	Direct/financial layer	Partial/reinforcement or system-cost extension	Direct or derivable	Partial/redispatching cost
CAPEX and OPEX	Partial	Direct	Partial	Direct or derivable	Partial
Net present cost (NPC)	Derivable if assumptions are harmonised	Derivable from CAPEX/OPEX and lifetime assumptions	Not direct	Derivable	Not direct
Levelised cost of electricity (LCOE)	Derivable at aggregate level	Derivable if annualised costs and useful energy are reported	Not direct	Derivable if energy served is included	Not direct
Return on investment (ROI)	Partial/policy scenario interpretation	Direct	Not direct	Direct or derivable	Not direct
Payback time	Not direct	Direct	Not direct	Derivable	Not direct
Renewable share	Direct/scenario-level	Direct or derivable	Partial/connection potential	Partial	Derivable
Renewable curtailment	Not operationally represented	Direct or derivable	Partial/constraint-related	Partial	Direct
CO_2 emissions/avoided emissions	Direct/scenario-level	Direct	Partial/if emission factors are linked	Partial/if emission factors are linked	Partial/if redispatch emissions are linked
Energy not served (ENS)	Not direct	Derivable if unmet demand is modelled	Not applicable	Possible extension	Not direct
Loss of load probability (LOLP/LPSP)	Not direct	Possible extension	Not applicable	Possible extension	Not direct
Autonomy hours	Not direct	Derivable for storage-based local systems	Not applicable	Derivable for BESS scenarios	Not direct
Voltage violations	Not direct	Not direct unless grid constraints are added	Direct	Direct or partial	Direct

(Continued)

Table 5 (continued)

KPI/Indicator	CEPIA	GREENADVISE	Hosting Capacity	Optimal Storage Placement	PowSyBl-METRIX
Line/transformer loading	Not direct	Not direct	Direct	Direct	Direct
Network losses	Not direct	Not direct	Direct	Direct	Direct or derivable
Storage state of charge	Not direct	Direct if batteries are included	Not direct	Direct	Direct
Storage siting and sizing	Not direct	Limited/user-defined system design	Not direct	Direct	Input-dependent
Redispatching cost	Not direct	Not direct	Not direct	Possible extension	Direct

Note: “Direct” indicates that the KPI is explicitly produced by the tool. “Derivable” indicates that the KPI can be calculated from available outputs if assumptions are harmonised. “Partial” indicates that the tool captures only part of the indicator or captures it at a different temporal/spatial scale. “Not direct” indicates that the KPI is outside the present implementation.

3.3 Lifecycle and Long-Term Techno-Economic Representation

Lifecycle representation remains uneven across the EMERGE toolbox. GREENADVISE includes a long-term financial layer that evaluates investment performance over a 20-year horizon through indicators such as return on investment and payback time. Optimal Storage Placement can include long-term discounted cash-flow logic through net present value and annual revenue/cost terms linked to operational battery dispatch. However, degradation-aware modelling, component replacement scheduling, discount-rate assumptions, and salvage-value treatment are not yet harmonised across all tools. As a result, the current cross-model comparison is strongest for operational resolution, network constraints, curtailment, and KPI structure, while lifetime asset representation remains less consistent. This is a relevant limitation because battery degradation can substantially affect the optimal sizing and economic performance of storage systems in microgrid applications; recent work has therefore proposed BESS planning approaches that explicitly account for lithium-ion capacity degradation when determining optimal storage size and operation [22].

In particular, affordability and tariff design in off-grid systems require consistent assumptions on discount rate, project lifetime, component replacement, battery degradation, residual value, diesel or backup-fuel costs, and the economic penalty assigned to unmet demand. Without this harmonisation, two tools may identify different “optimal” configurations because they optimise different cost boundaries rather than because the underlying system performance differs. This limitation is particularly relevant for mini-grid applications, where battery degradation, inverter replacement, diesel-generator lifetime, and tariff evolution can strongly affect long-term affordability. Future integration of the EMERGE toolbox should therefore prioritise a harmonised lifecycle module covering degradation, replacement cycles, discounting, residual value, and sensitivity analysis on financing assumptions.

4 Discussion

The comparison confirms that the EMERGE toolbox should be interpreted as a multi-scale modelling ecosystem rather than as a set of interchangeable optimisation tools. The key distinction among the tools has already been established Section 2; therefore, the Discussion focuses on the implications of this structure for developing-country mini-grid and grid-edge planning. The main implication is that no single tool captures all planning dimensions simultaneously. Instead, the toolbox combines long-term scenario analysis, local techno-economic optimisation, hosting-capacity assessment, storage planning, and constrained network operation. This differentiation is important for developing-country contexts. In regions such as Mozambique, Morocco, Mali, and Nigeria, resource potential is often high, but energy planning is constrained by weak grids, dispersed rural demand, affordability, limited data availability, and institutional capacity. Under these conditions, long-term national models can identify strategic transition directions, but they cannot replace operational tools able to test whether renewable generation can actually be absorbed by local networks. Conversely, detailed grid and community tools provide operational insight but require input assumptions and policy scenarios that are often generated at broader system scale. The practical value of the EMERGE toolbox therefore lies in the combination of these modelling layers.

A further limitation of the present comparison is that the tools were not tested on a single harmonised fully islanded mini-grid benchmark. Such a benchmark would be useful to compare PV-battery-backup sizing, hourly reliability, loss of load, storage autonomy, curtailment, lifecycle cost, and tariff sensitivity under identical input assumptions. This is identified as a priority for future EMERGE toolbox integration.

The comparison also highlights a trade-off between model breadth and operational detail. CEPIA provides broad multi-sectoral coverage but limited operational resolution. GREENADVISE captures hourly renewable variability and financial performance at small scale but does not represent full network physics. Hosting Capacity and PowSyBl-METRIX capture network constraints and curtailment but are less focused on household-level affordability and long-term investment recovery. Optimal Storage Placement bridges investment and operation for BESS but requires reliable network data and assumptions on costs, revenues, and battery operation. These complementarities suggest that mini-grid and grid-edge planning should not rely on a single model; instead, scenario, community, storage, and network tools should be linked through harmonised data structures and shared KPIs.

This distinction is important because grid-constrained tools may overemphasise voltage, congestion, and line-loading bottlenecks when applied to fully isolated mini-grids. Conversely, purely techno-economic community tools may underrepresent network feasibility when renewable projects are connected to weak distribution grids. The appropriate modelling chain therefore depends on the system boundary: islanded mini-grids require dispatch, storage autonomy, backup generation, and reliability metrics, whereas grid-edge systems require additional network-security and hosting-capacity assessment.

Overall, the comparison confirms that the EMERGE toolbox should be used as a multi-scale modelling ecosystem rather than as a set of interchangeable optimisation tools. CEPIA supports long-term policy and sectoral pathway analysis, but it cannot capture hourly loss-of-load events or real-time PV-storage-backup balancing. GREENADVISE and Optimal Storage Placement provide stronger operational and techno-economic detail, while Hosting Capacity and PowSyBl-METRIX are most suitable for weak-grid and network-constrained renewable integration studies. Therefore, fully islanded mini-grid design requires harmonised assumptions on demand, renewable profiles, storage, backup generation, reliability, component lifetime, discounting, and affordability. A dedicated islanded benchmark with common KPIs such as LCOE, NPC, cost of unmet demand, renewable curtailment, and emissions is recommended as a future validation step.

5 Conclusion

This paper reviewed and compared five EMERGE modelling tools for mini-grid and grid-edge planning in developing-country contexts: CEPIA, Hosting Capacity, Optimal Storage Placement, GREENADVISE, and PowSyBl-METRIX. To address the need for a more technically grounded comparison, the paper introduced a generalized techno-economic optimisation framework covering investment, dispatch, storage, reliability, emissions, and network constraints. This framework made it possible to compare the tools according to objective functions, decision variables, temporal and spatial resolution, solver structure, economic representation, and treatment of renewable variability and local constraints.

Future work should also include a fully islanded benchmark case with harmonised demand, renewable-resource, storage, backup-generation, reliability, and cost assumptions. This would allow the relative strengths and limitations of each modelling approach to be assessed under strictly comparable off-grid conditions.

The results show that the EMERGE toolbox provides complementary rather than redundant capabilities. CEPIA supports long-term national scenario and policy assessment; GREENADVISE supports household and community-level techno-economic optimisation; Hosting Capacity evaluates renewable integration limits; Optimal Storage Placement identifies technically and economically relevant BESS siting and sizing options; and PowSyBl-METRIX assesses constrained dispatch, curtailment, congestion, and flexibility operation. Representative examples, including the Mozambique PowSyBl-METRIX test case, show how network-constrained tools can quantify the curtailment and redispatching implications of storage integration.

The main contribution of the EMERGE toolbox is therefore the creation of an interoperable modelling ecosystem that links policy pathways, local renewable investment, storage planning, and grid-operation constraints. This is particularly relevant for African energy planning, where renewable-resource availability, weak grids, affordability, rural load dispersion, and institutional constraints must be considered together. Future work should strengthen cross-tool integration through harmonised data formats, shared KPI definitions, a common lifecycle-cost module, and expanded validation using calibrated pilot-site data. A fully islanded benchmark case with harmonised demand, renewable-resource, storage, backup-generation, reliability, and cost assumptions is also recommended to support future cross-tool validation under strictly comparable off-grid conditions.

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Abbreviations

The following abbreviations are used in this manuscript

AU African Union

CSA Common System Architecture
GDP Gross domestic product
IAM Integrated Assessment Model
R&D Research & Development
SSA Sub-saharan Africa
TSO Transmission system operator

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