Energy System Modelling for Green Development of Africa

Grant Agreement N° 101118278

D2.1 – Common System Architecture

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Lead Beneficiary: CARTIF

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D2.1 – Common System Architecture

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Revision and history chart

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Executive summary

The Deliverable D2.1 Common System Architecture (CSA) provides a comprehensive overview of the system architecture designed for the EMERGE Toolbox, with a focus on addressing the energy-related challenges and opportunities specific to the African context. The report begins by introducing the purpose of the document, explaining its connection to other project activities and acknowledging the contributions of participating partners. It proceeds with an in-depth analysis of the African pilot sites, where historical data, trends, and sector-specific information are used to identify challenges and opportunities relevant to sustainable development goals. This section also considers newly developed laws and policies to further support the CSA's design.

Next, the report reviews existing energy-related models, databases, and ongoing collaborative projects between Europe and Africa. The aim is to evaluate historical trends in energy consumption and production, providing insights into strengths, weaknesses, and potential synergies that could aid decision-makers in the energy sector. The methodology section follows, detailing the process used to define the CSA. It begins with the identification of commonly used features and variables from existing open tools and energy models, aiming to pinpoint synergies between different components of the EMERGE Toolbox.

The development of the EMERGE database is then discussed, highlighting its functional role within the Toolbox and detailing the main data categories, technical design aspects, and the current status of module interconnection. The report concludes with a summary of the key findings and a bibliography of sources referenced throughout the document. Overall, this deliverable provides a structured approach to understanding the CSA in the context of Africa's energy landscape and the ongoing development of the EMERGE Toolbox.

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Abbreviations

Abbreviation	Definition
AT	Austria
AU	African Union
BESS	Battery Energy Storage Systems
BU	Bottom-Up model
CSA	Common System Architecture
CV	Cape Verde
D	Deliverable
ES	Spain
ESMs	Energy System Models
EU	European Union
FR	France
GDP	Gross Domestic Product
HR	Croatia
IT	Italy
IAM	Integrated Assessment Model
KPIs	Key Performance Indicators
ML	Mali
MO	Morocco
MZ	Mozambique
NI	Nigeria
R&D	Research and Development
SSA	Sub-Saharan Africa
T	Task
TD	Top-Down model
WP	Work Package

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1. Introduction

The EMERGE project seeks to provide African policymakers, academics, investors, and citizens with the necessary tools and knowledge to increase clean energy production and sustainable resource use while addressing social, climatic, economic, and technical constraints.

To achieve this, EMERGE will leverage successful digital solutions from the EU to create robust, user-friendly tools for promoting environmentally-friendly and cost-effective energy planning for both EU and AU policymakers. These tools will evaluate energy policies and support decision-makers by considering different sectors through cross-sectoral integration. EMERGE's methodology involves an iterative process of co-design, development, piloting, and assessment, which will be supported by pilot sites.

This project will focus on three different African regions (listed below) to develop knowledge communities through a participatory approach. By bringing innovative solutions, knowledge transfer, and capacity-building approaches, EMERGE aims to address practical problems and improve the quality of life and sustainability of solutions across African communities.

- North-Western Africa (Morocco)
- East Africa (Mozambique)
- Niger river region (Mali/Nigeria)

In this framework the *Common System Architecture* (CSA) will facilitate the iterative cross-sectoral integration process by providing insights into economic, technical, social, and environmental parameters, as well as energy infrastructure constraints *Figure 1*, that will be implemented on the *EMERGE Toolbox*. The *EMERGE Toolbox*, central to the project, consists of a set of methods, algorithms, tools, and platforms that support development and analysis of energy systems based on green technology at a large scale. The tools support flexible energy asset integration, data analysis, and advanced decision-making algorithms, all designed to increase renewable energy penetration and efficiency.

Additionally, an *open database* will support the Toolbox integrating *CSA* findings to represent social, economic, environmental, and technical context, enhancing the implementation of new test cases and knowledge sharing.

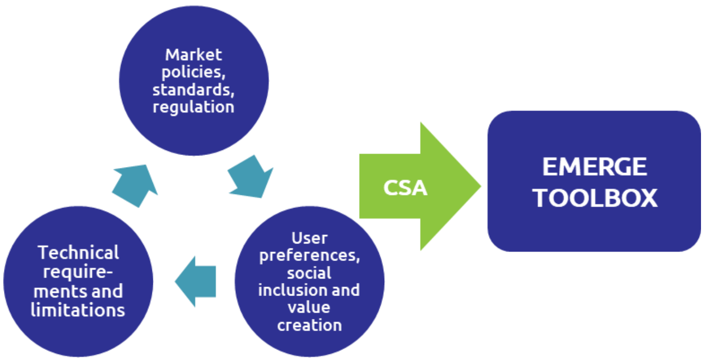

Figure 1 - The know-how generated in EMERGE for the design of the EMERGE Toolbox

The project aligns with the principles of the Africa-Europe Alliance [1] and the EU-AU R&I Partnership on Climate Change and Sustainable Energy [2], aiming to develop energy models suitable for Africa's unique contexts. It will also follow BRIDGE [3] initiative's guidelines for scalability and replicability to facilitate large-scale implementation.

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1.1. Structure of the deliverable

This deliverable *D2.1 Common System architecture*, is structured into the following key sections:

<u>*Section 1*</u> introduces the purpose of the report, main relation to other activities, and the contribution of participating partners on this document

<u>*Section 2*</u> includes an analysis of the context of pilot sites, to identify the different challenges and opportunities to be addressed on the *Common System Architecture* (CSA); based on historical data, trends, and sector-specific information, as well as newly developed laws and policies relevant to sustainable development goals.

<u>*Section 3*</u> includes a review and analysis of existing energy-related models and databases in Africa, as well as ongoing projects featuring collaboration between Europe and Africa to evaluate energy policies and support decision-makers; with the aim to explore key historical trends in energy consumption and production; identifying strengths, weaknesses and potential synergies.

<u>*Section 4*</u> defines the methodology used for *Common System Architecture* (CSA) definition, starting with the identification of most commonly used features and variables in similar existing open tools and energy models that evaluate energy policies to support decision-makers, and identify potential synergies between the different components of the EMERGE Toolbox.

<u>*Section 5*</u> offers an overview of the development of the EMERGE database, including a description of their functional role as part of the EMERGE Toolbox, and main categories of data that will be stored in the database. Then, technical aspects of the database design stage and a scheme of interconnection between modules was included.

<u>*Sections 6 and 7*</u> include the main conclusions from this document as well as the bibliography used as reference.

1.2. Relation to other tasks

Figure 2 shows the main inputs and outputs of Task 2.2 *Defining a Common System Architecture (CSA)* and the relation with other project's Work Packages (WPs) and tasks.

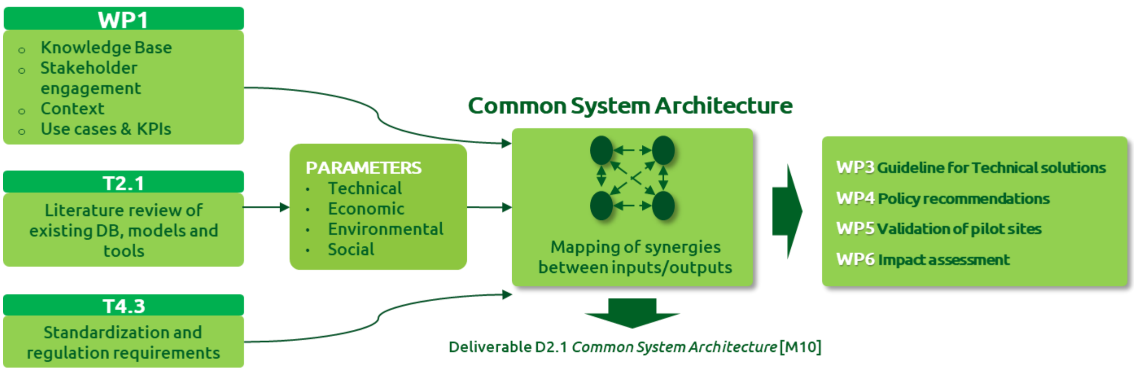

Figure 2 - Common System Architecture (CSA) relation with other tasks

Main inputs for the CSA come from **T2.1** *Analysis of existing databases and models* and **WP1** *EMERGE Knowledge Base, engagement and value-based proposition design of the energy system models.* Then, the CSA will select from those tasks the most relevant technical, economic, environmental and social parameters, to adapt energy system models to the African context. These parameters will be identified through a codesign process which will involve citizens and relevant stakeholders from the energy sector value-chain, as well as from literature review of similar projects and models.

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Task 2.2 will also integrate standardization and regulation constraints identified on **T4.3** *Steering policy and market recommendations,* as well as insights on the EMERGEs' tools effects over environmental, social, regulatory and economic conditions, gathered through co-design workshops as part of *T4.2 EMERGE R&I and Policy lab.*

The outputs of this tasks are the set of parameters of the CSA framework and identified synergies and interlinkages to be applied on the *EMERGE ToolBox*, and this current deliverable D2.1, which will in turn be used as a guideline for the development of technical solutions in **WP3** *EMERGE Toolbox development*, policy recommendations in **WP4** *Research & Innovation and Policy Laboratory*, validation on pilot sites in **WP5** *Demonstration and validation of the EMERGE solution* and impact assessment in **WP6** *Dissemination, exploitation and impact creation*.

This deliverable D2.1 is the initial version of the CSA, which will be updated on deliverable *D2.2 Database* due for M24 (November 2025), to incorporate feedback from the pilots after testing the tools on their demo sites.

1.3. Contribution of partners

This subsection details the structure of the document, as well as the detailed contribution from each EMERGE partner on this document:

Table 1 - Table of contributing partners

Partner	Short name	Country
University of Zagreb – Faculty of Mechanical Engineering and Naval Architecture	UNIZAG	Croatia (HR)
EnGreen Srl	EnGreen	Italy (IT)
Fundación CARTIF	CARTIF	Spain (ES)
Fundación CIRCE	CIRCE	Spain (ES)
Artelys	Artelys	France (FR)
African Technology Innovation Hubs	AfriLabs	Nigeria (NI)
European Sustainable Energy Innovation Alliance	ESEIA	Austria (AT)
Ecowas Centre for Renewable Energy and Energy Efficiency	ECREEE	Cape Verde (CV)
Universidade Eduardo Mondlane	UEM	Mozambique (MZ)
Brain Information Technologies	BrainIT	Croatia (HR)
Universite Mohammed Premier 1	UMP	Morocco (MO)

- **CARTIF**: Preparation of the structure and main contents of this deliverable, as leader of Task 2.2 *Defining a Common System Architecture (CSA)*
- **ECREEE**: Identification and analysis of open data sources and similar models, as well as identification of energy modelling data needs as leader of Task 2.1 *Analysis of existing databases and models*, with the support of **CARTIF** for the identification of similar ongoing European projects and initiatives.
- **Artelys**, **CIRCE** and **UNIZAG**: collaboration on CSA definition led by **CARTIF**, including tool description, features identification and mapping of inputs, outputs and synergies between Toolbox, as tool developers on WP3 *EMERGE Toolbox development*
- **EnGreen**: use cases and pilot sites characterisation, identification of specific challenges and goals to be covered and demonstrated by EMERGE project scope, with the contribution of pilot site leaders **UEM**, **UMP** and **ECREEE** as part of WP5 *Demonstration and validation of the EMERGE solutions*
- **BrainIT**: Preliminary design and structure of EMERGE open-database, as leaders of Task 2.3 *EMERGE database development*
- **AfriLabs** and **ESEIA** as deliverable content reviewers

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2. Energy modelling in African Union

The 21st century presents both challenges and opportunities for the African continent in terms of socioeconomic expansion and development. With an expected population growth of around 1.14 billion people by 2050, achieving a balanced and equitable growth will hinge on ensuring affordable and universal access to electricity [4]. Africa's vast natural resources provide a unique opportunity to drive energy expansion rooted in clean and sustainable energy sources. However, realizing this potential requires substantial investment from governments and institutions.

In this context, energy modelling becomes a critical and indispensable tool. It serves as the most robust and reliable method for guiding government decisions, helping to identify the optimal steps in a roadmap that aims to connect the entire population to electricity, either through grid connection or stand-alone installations.

Furthermore, the transition to a more sustainable energy infrastructure in Africa not only addresses the need for electricity access but also has the potential to drive economic development, reduce poverty, and enhance climate resilience. As energy demand continues to rise with population growth and economic expansion, it is crucial for governments to have tools that allow them to anticipate future scenarios, optimize the use of natural resources, and minimize environmental impacts. Energy modelling, therefore, not only helps in planning grid expansion but also facilitates the integration of renewable energy sources, ensuring that energy growth is both sustainable and beneficial for all communities.

Along with EMERGE, other EU-funded projects aim to improve energy modelling in Africa, such as ONEPlanET [5], OpenMod4Africa [6] and RE-Integrate [7]; by studying different case studies and demo-sites. Collaboration between projects will be necessary to achieve representative and effective energy models. In this case EMERGE concept is built under three relevant case studies in Africa (*Figure 3)* that represent different context (social, economic and technical); ensuring broad replicability of the EMERGE solutions under different grid and energy infrastructures:

- North-Western Africa (Morocco)
- East Africa (Mozambique)
- Niger river region (Mali/Nigeria)

Figure 3 - EMERGE map of pilot sites

In the next subchapters a summary of the pilots' general and energy context is given, along with an overview of national goals plans and challenges to be addressed by EMERGE project; a summary is given in *Table 2*, *Table 3* and *Table 4.* The context of pilot sites has been further detailed in project's deliverable *D5.1 – Pilots and use cases (PUC)* [8].

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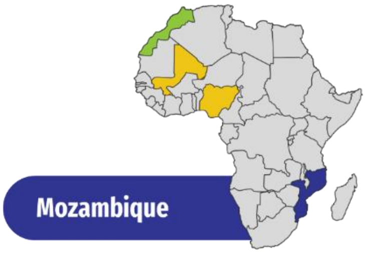
2.1. Mozambique



Mozambique is located in the Southern Hemisphere, on the southeast coast of the African continent. Administratively, the country is divided into 11 provinces, including the municipality of Maputo City, the capital, which has provincial status. The provinces are further divided into 154 districts. The country has an estimated population of 34.6 million (2024), with about 59% living in rural areas and population density of 44 people per km^2 [9]. Mozambique covers an area of 801,590 km^2 of land and approximately 13,000 km^2 of inland water. Along its roughly 2,700 km of coastline, there are numerous islands. Mozambique has a GDP per capita of USD 659.1 and a total GDP of USD 22.98 billion in 2024 [10].

Mozambique has abundant renewable energy resources, including high solar radiation with values between 1,785 and 2,206 kWh/m^2/year, particularly in Cabo Delgado, Nampula, Tete, and Niassa, with Tete nearing global solar benchmarks. The country possesses significant hydropower potential too from its 13 major river basins, currently providing 99% of its renewable electricity generation, though it faces challenges from climate variability affecting water resources. Wind energy also shows promise, with average wind speeds of 6-7 m/s along the coast and up to 8 m/s at higher elevations. Coastal areas like Ponta de Ouro and Mavelane are particularly favourable but not exploited at all. Biomass is a major energy source, accounting for about 80% of total consumption, primarily for residential and industrial use. Mozambique's potential for biomass-based electricity is estimated at over 2 GW [11].

- **Energy context:**

The country's reliance on biomass for energy, driven by inadequate grid infrastructure and high costs, is further straining natural resources and the environment as urban and rural expansion intensifies. Most of Mozambique's energy comes from renewable resources, currently 99% of the renewable electricity generation comes from hydropower, which is vulnerable to climate variability and affects the country's energy exports. There is substantial potential to diversify the energy mix by incorporating wind and solar energy, which currently contribute minimally. Expanding these renewable sources like PV generation plants, could address energy challenges, especially for rural areas underserved by the grid, aligning with broader global sustainability goals.

Energy access is still a major challenge for the country energy context: efforts to increase electrification have seen the rate rise from 5% in 2001 to 44% in 2022, though access remains low, especially in rural areas. In 2022, only 79.4% of the urban population in Mozambique had access to electricity, compared to just 5% of the rural population, where 63% of Mozambicans live. This is far below the global average of rural electricity access, which stands at 84% [12]. The national grid reaches about 30% of the population, but many district capitals rely on costly and unreliable diesel generators. Most rural households, schools, health centres, and administrative posts lack electricity, which hampers agricultural production and access to modern amenities.

In Mozambique, the most energy-intensive sectors include the residential sector, industry—particularly aluminium production and extractive industries—and transport. Among the most pollutant sectors are the broader (1) energy industry, encompassing charcoal production, natural gas processing, and coal mining; (2) transport; (3) biomass combustion in households (such as wood and charcoal); (4) power generation; and (5) manufacturing. In 2023, the country's electricity generation capacity will total 2.8 GW, with 80% coming from renewable sources—79% from hydropower, 1% from solar, and smaller contributions of other RES [11].

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- **Goals trends and challenges:**

Mozambique's transition to green energy presents significant opportunities and challenges. The country has substantial potential in renewable energy sources, such as solar, wind, biomass, and hydro, which could enhance energy access and contribute to a sustainable energy transition if effectively harnessed. However, the path to this transition is constrained by several limitations. Chief among these are inadequate energy planning, insufficient investment in the sector, and the lack of robust energy infrastructure, particularly strong transmission interconnections. Additionally, the sparse population density and low urbanization, combined with widespread energy poverty, further hinder progress.

Barriers to green energy transition include the lack of financial resources to properly invest, inadequate power infrastructure, and the high connection fees to the national grid, which discourage both residential and industrial users. Rural areas are particularly disadvantaged, with only 5% of the population having access to electricity, compounded by a lack of investments in rural electrification and disconnected regions from the grid. Furthermore, the absence of a transparent regulatory framework impedes effective policy implementation and investor confidence.

The downside of this transition is the economic impact of moving away from fossil fuels, particularly natural gas, which Mozambique has recently begun to explore for its potential in national use and export revenue. Transitioning from these fossil fuel resources could significantly affect both the national economy and revenue streams, presenting a major trade-off in the shift toward green energy.

Some goals and challenges from Republic of Mozambique: Poverty Reduction and Growth Strategy. Retrieved from National Development Strategy (NDS) for 2025-2044 [13] are included in the summary *Table 2*.

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Table 2 - Summary table of demo site context, Mozambique

MOZAMBIQUE			
GENERAL CONTEXT	Distribution		11 provinces and 154 districts
	Population		34.6 million (2024)
	Population density		44 (people per sq. km land area) (2024)
	Rural population		About 59%, 20.4 million (2024)
	Total GDP		22.98 USD billion in 2024, with real GDP growth of4.97 % annual
	GDP per capita		659.USD per capita in 2024
ENERGY CONTEXT	Installed capacity		2.8 GW in total (2023); where hydropower 2.2 GW (79%) and solar energy 75 MW (1%),
	Electrification rate		From 5% in 2001 to 44% in 2022
	Energy access		In 2022, 79.4% of the urban population had electricity compared to just 5% of the rural population, where 59% of Mozambicans live.
	Renewable energy potential	Solar radiation	From 1,785 to 2,206 kwh/m²/year
		Hydropower potential	Currently 99% of its renewable electricity generation
		Wind energy	Average wind speeds of 6-7 m/s along the coast and up to 8 m/s at higher elevations
		Biomass	Estimated biomass-based electricity potential of 2GW
	Most energy-intensive sectors		Residential sector, industry—particularly aluminium production and extractive industries—and transport.
	Most pollutant sectors		Energy industry (charcoal production, natural gas processing, and coal mining); transport; biomass combustion in households; power generation; and manufacturing.
NATIONAL GOALS	Improving power infrastructures: rehabilitation, maintenance and building new infrastructures.		
	Diversification of the energy matrix with a focus on the expansion of renewable energy and energy efficiency.		
	Promote the energy transition by reducing dependence on coal and oil, expanding the participation of renewable energies and mitigate the impacts of climate change, while creating new business opportunities and jobs in the renewable energy sector.		
	Also, targets from the National Development Strategy 2025-2044 [13] from 2024 values to 2043 objective: - Increase installed capacity to enable the generation of 73,000 GWh - Population with access to public grid power from 39.0%, to 100% - Population using firewood as fuel for cooking from 71.9% to 42.2%		
MAIN CHALLENGES	Inadequate power infrastructure, with high connection fees		
	Energy access is still a major challenge, especially for rural areas where only 5% of the rural population (Lack of investment)		
	Lack of a transparent regulatory framework for effective policy implementation and investor confidence.		
	Sparse population density and low urbanization, combined with widespread energy poverty, further hinder progress		

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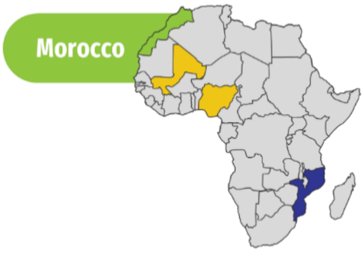
2.2. Morocco



Morocco has a population of approximately 38.1 million people in 2024 [9] and covers an area of 446,550 km². The country is divided into 12 regions, 62 provinces, and 13 prefectures.
In 2023, Morocco's economy grew by 3.02%, recovering from 1.3% growth in 2022, thanks to a rebound in agriculture and services. Morocco has a GDP per capita of 4.08 thousand USD per capita and a total GDP of 152.38 billion of USD in 2024 [10].

Morocco is well-positioned to harness renewable energy due to its substantial natural resources. The country benefits from abundant sunlight, receiving over 3,000 hours of sunshine annually and an irradiation of approximately 5 kWh/m²/day. This results in a solar energy potential estimated at around 500 TWh per year, covering both photovoltaic and solar thermal applications. Additionally, Morocco has significant wind energy potential, with estimates suggesting a capacity of nearly 25 GW. These advantages place Morocco in a strong position to advance its renewable energy sector and contribute significantly to its green energy goals.

- **Energy context:**

Morocco still depends on depends upon imports and fossil fuels, which account for approximately 68% of installed capacity in Morocco, with the remaining 32% from renewable energy sources: hydro, wind, solar [14], but it is becoming a leader in renewable energy development; increasing the share of renewable energy (including hydropower) from 6% in 2000 to 19% in 2020, aligning with figures from France and Tunisia but falling short of Spain and Portugal. By 2019, Morocco generated about half of North Africa's electricity from renewable sources. The country also made substantial progress toward its goal of 42% renewable energy capacity for electricity generation by 2020, achieving 37% despite challenges such as the COVID-19 pandemic and various technical and institutional obstacles. The most energy-intensive sectors are the building sector, which accounts for 36% of energy consumption (8% for tertiary and 28% for residential buildings), transportation at 35%, industry at 19% and agriculture at 8% [15].

To support the green energy transition, Morocco has implemented several key plans and strategies. Legislative and regulatory developments are underway, alongside national initiatives such as the renewable energy development plan, the energy efficiency plan, and various programs like:

- Morocco's National Strategy for Sustainable Development (NSSD) [16] aims to transform the Moroccan economy into a green and inclusive economy by 2030 following the principles of sustainable development goals [17], aiming to reduce dependence on fossil fuels, increase the use of renewable energy, protect natural resources through sustainable management practices, and promote circular economy.
- Contribution Determined at National Level (CDNL) [18], with a total reduction objective in GHG emissions by 2030 of 42% (17% unconditional and additional conditional of 25%).
- Plan Climate National 2020-2030 (PCN) [19], constitutes the coordination base and development framework for a medium- and long-term climate policy that will enable a proactive and ambitious response to the challenges posed by climate change in the Moroccan context.
- National Air Program (PNAir) plan for 2018-2030 [20], aims to prevent and reduce atmospheric emissions from fixed and mobile sources, focusing on transport and industry.
- National Energy Strategy (2009) [21], aims to increase the share of renewable energies to 52% by 2030.

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- Plus, Morocco is a member of the Climate and Clean Air Coalition (CCAC) [22] and the International Solar Alliance (ISA) [23].

Generally, Morocco's green energy transition strategies involve diversifying and optimizing the energy mix with solar, wind, hydro, and biomass, enhancing electricity exchanges with neighbouring countries for stability, and ensuring that energy projects meet environmental and social standards. The country is also prioritizing energy efficiency through building renovations, appliance standardization, and public transportation promotion.

- **Goals trends and challenges:**

Morocco is making significant steps forward in its green energy transition, with notable progress in recent years. The country has invested heavily in major renewable energy projects such as the *Noor solar complex*, composed of three Concentrated Solar Power (CSP) plants and one PV plant with a total installed capacity of 580MW; and the *Tarfaya wind farm* with a capacity of 300MW; showcasing Morocco's commitment and financial capability. Morocco aims to boost the share of renewables in its energy mix to 52% [21] by 2030 and has created a supportive regulatory environment, including incentives like guaranteed feed-in tariffs, to encourage private investment and facilitate the integration of renewable energy. Public awareness and mobilization efforts are also in place to foster a sustainability-oriented culture. However, achieving a fully renewable energy system by 2050 remains uncertain. While some optimistic reports suggest a significant transition of 75% to 85% is achievable, this relies on technological advancements, continuous investment, and supportive policies. The country faces key challenges, including reducing reliance on fossil fuel imports, stimulating local economic growth and job creation, establishing comprehensive frameworks for policy development, education, and research, and enhancing community engagement to support these objectives.

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Table 3 - Summary table of demos site context, Morocco

MOROCCO			
GENERAL CONTEXT	Distribution	12 regions, 62 provinces, and 13 prefectures	
	Population	38.1 million (2024)	
	Population density	85 (people per sq. Km land area) (2024) [9]	
	Total GDP	152.38 billion of USD in 2024	
	GDP per capita	4.08 thousand USD per capita in 2024 [10]	
ENERGY CONTEXT	Installed capacity	Total installed capacity of 10.63 GW, of which 52% Coal thermal plant, 14% Gas turbines, 12% Hydropower, 11% Wind power, 5% Concentrated solar power (CSP) and 2% of PV, plus other sources.	
	Share of renewables	From 6% in 2000 to 19% in 2020	
	Energy access	100% in2024 [24]	
	Renewable energy potential	Solar radiation	Estimated potential of 500 TWh/year
		Wind energy	Estimated capacity of 25 GW.
	Most energy-intensive sectors	Building sector accounts for 36% of energy consumption, transport 35%, industry at 19% and agriculture at 8% on 2020.	
NATIONAL GOALS	Increase share of renewable energies to 52% by 2030 -> National Energy Strategy (2009)		
	Diversifying and optimize the energy mix other reenable sources and enhancing electricity exchanges with neighbouring countries		
	Prioritizing energy efficiency through building renovations, appliance standards, and public transportation promotion		
	GHG emissions reduction for 2030, base of 17% plus an additional 25%, total of 42%. -> Contribution Determined at National Level (CDNL)		
MAIN CHALLENGES	Reducing reliance on fossil fuel imports		
	Promoting local economic growth and job creation,		
	Establishing comprehensive frameworks for policy development, education, and R&D,		
	Enhancing community engagement to support these objectives		

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2.3. Niger river region (Mali/Nigeria)

The Niger River, Africa's third-longest river, plays a critical role in the socio-environmental landscape of West Africa. Originating in the Guinea Highlands, it flows through Mali, Niger, and Nigeria, before emptying into the Gulf of Guinea via the Niger Delta. The river's 2,117,700 km² drainage basin is not only essential for agriculture, transportation, and hydropower generation, but it also contains much of Nigeria's petroleum reserves, making it a vital economic artery. For countries like Mali and Nigeria, the Niger River is both a source of life and a crucial element in their respective energy systems, with several dams constructed along its course to harness hydropower [25].

2.3.1. Mali

Mali is the second largest country in West Africa, covering 1,241,238 km² of land area, with an estimated population of 24.5 million (2024) and a population density of 20 pp/km^2 [9]; the nation faces significant challenges due to its geographic and environmental conditions, particularly drought and desertification. Mali's economy is primarily agrarian, and its GDP per capita stands around 0.9thousand USD in 2024 [10], highlighting the need for substantial development in various sectors, including energy. This is reflected in the country's energy consumption patterns, where the residential sector accounts for 72.5%, followed by services at 13.5% and industry at 5.4% [26].

- **Energy context:**

In terms of energy, Mali remains largely underdeveloped, with only 59% of the urban population and 14% of rural inhabitants having access to electricity. In 2021 installed capacity was around 0.94 GW, and only 21,2% from renewable sources, with the majority generated by hydropower, around 92%, while the other sources like solar and wind represents 4% and the other 4% for biofuels [24].

Despite the challenges, Mali has made notable progress in implementing mini-grids as the least-cost solution to increase energy access in remote areas. Currently, more than 150 mini-grids are in operation, although most of these small power producers rely on diesel-fuel generating units, which come with high production costs. To support this expansion, Mali’s rural energy agency, AMADER (Agence Malienne pour le Dévéloppement de l’Energie Domestique et de l’Electrification Rurale), provides subsidies to help connect new customers [27].

- **Goals trends and challenges:**

Mali’s National Renewable Energy Action Plan (PANER) outlines ambitious goals for increasing renewable energy capacity. By 2030, the country aims to achieve a nine-fold increase in renewable capacity, reaching 1.42 GW. This strategy is bolstered by measures like tax exemptions on solar and wind technologies, encouraging private sector investment in clean energy [26]. However, Mali continues to grapple with environmental challenges, including land degradation and water scarcity, exacerbated by the impacts of climate change. In response, Mali has committed to reducing emissions under its Nationally Determined Contributions (NDCs), targeting a 20% reduction in emissions below Business-as-Usual (BAU) levels by 2030 [28].

2.3.2. Nigeria

Nigeria, Africa’s most populous country with an estimated population of 232.7 million (2024) and a population density of 255 pp/km^2 [9]. Nigeria stands as one of the largest economic drivers in Africa, with a GDP per capita of 1.11 thousand USD and a total GDP of 252.74 billion of USD [10], it has

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immense potential for growth, but faces significant developmental challenges, particularly in the energy sector.

- **Energy context:**

Although Nigeria possesses vast energy resources, particularly in oil, gas, and renewable energy, it struggles to meet the energy demands of its growing population. In 2021, Nigeria had an installed energy capacity of 13.25 GW, from which only 11.21% is electricity generated from renewable sources, mainly Hydropower and the rest from gas-fired plants. Access to electricity remains uneven, with only 59.5% of the population having access as of 2021, and rural areas significantly under-served with less than 23% [24].

Nigeria has an enormous energy potential, in particular from solar radiation with an average of 5,535 kWh/m^{2}day [29].Furthermore, there are 1800 m^3/per capita year of renewable water resources available for a total exploitable potential of hydropower at over 14.1 GW, with major dams like Kainji, Shiroro, Zungeru, and Jebba [30].

- **Goals trends and challenges:**

Nigeria's energy strategy for the future is ambitious. By 2030, the government aims to achieve 90% electricity access [31] and increase the share of renewable energy to 36% of total generation up from 23% in 2022 [32]. The goal is to increase electricity production capacity.to 30 GW, with 13.8 GW coming from grid-connected renewable energy sources, including medium and large hydropower. Solar energy is also poised to play a major role in achieving these targets, particularly in rural electrification through clean energy mini-grids [33]. In addition to addressing its energy deficit, Nigeria is committed to reducing emissions, targeting a 20% unconditional and 45% conditional reduction below BAU levels by 2030 under its NDCs [34].

Conclusion: Energy Transitions and Future Trends

Both Mali and Nigeria exemplify the diverse energy challenges and opportunities present in Africa today. Mali, despite its limited infrastructure, is advancing in rural electrification through innovative mini-grid solutions. Its focus on renewable energy, particularly hydropower, solar, and wind, aligns with broader continental goals of sustainable development. Nigeria, on the other hand, is a major energy producer but faces the challenge of meeting the demands of its rapidly growing population. With significant solar potential and plans to scale up renewable energy capacity, Nigeria is on a path toward a more resilient and sustainable energy future.

In the coming years, the integration of renewable energy, alongside advances in energy modelling and planning, will be crucial for both countries. As Africa's population and energy needs continue to grow, tools that enable governments to forecast and optimise energy usage will be vital for ensuring that future energy development is both inclusive and sustainable.

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Table 4 - Summary table of demo site context, Niger basin in Mali

<table>
<tr><th colspan="4">NIGER RIVER BASIN in Mali</th></tr>
<tr><td rowspan="5">GENERAL CONTEXT</td><td>Distribution</td><td colspan="2">19 regions, 819 municipalities and 12,712 villages</td></tr>
<tr><td>Population</td><td colspan="2">24.5 in 2024 [9]</td></tr>
<tr><td>Population density</td><td colspan="2">20 people per Km^2 (2024) [9]</td></tr>
<tr><td>Total GDP</td><td colspan="2">21.66 billion of USD in 2024 [10]</td></tr>
<tr><td>GDP per capita</td><td colspan="2">0.9 thousand USD in 2024 [10]</td></tr>
<tr><td rowspan="8">ENERGY CONTEXT</td><td>Installed capacity</td><td colspan="2">Total installed capacity in 2024 is 0.94 GW, with renewable energy accounting for only 21.2%, primarily hydropower, which represents over 90% of renewable electricity generation [24]</td></tr>
<tr><td>Energy access</td><td colspan="2">National access to electricity is 53.4%, reaching 96.9% in urban areas and only 18.3% in rural areas; clean access for cooking is also low with just 1.2% in 2024. [24]</td></tr>
<tr><td rowspan="4">Renewable energy potential</td><td>Solar radiation</td><td>From 5 to 7 kWh/m^2/day</td></tr>
<tr><td>Hydropower potential</td><td>Estimated to be 2.2 GW from all rivers (reference period 1998-2014)</td></tr>
<tr><td>Solar Energy</td><td>Total installed capacity of 97 MW (2023)</td></tr>
<tr><td>Wind energy</td><td>150 MW (to be installed on Rencore Energy)</td></tr>
<tr><td>Most energy-intensive sectors</td><td colspan="2">Residential sector, primary source is mainly wood and charcoal for cooking</td></tr>
<tr><td>Most pollutant sectors</td><td colspan="2">Air pollution due to dust storms and GHG emissions from transport, industry, livestock, energy, …</td></tr>
<tr><td rowspan="5">NATIONAL GOALS</td><td colspan="3">Reach 80% electricity access by 2030, of which urban access up to 100% and rural access up to 50%.</td></tr>
<tr><td colspan="3">Universal access to clean cooking by 2030.</td></tr>
<tr><td colspan="3">Increase on the electrification rate from 57% in 2022 to 87% in 2030</td></tr>
<tr><td colspan="3">Increase share in renewables on the energy mix for 37% in 2030 (including hydropower)</td></tr>
<tr><td colspan="3">CO_2 emissions reduction by 31% for energy, 25% for agriculture, 39% for land use and forestry, and 31% for waste sectors by 2030 as compared to the business-as-usual scenario.</td></tr>
<tr><td rowspan="4">NATIONAL GOALS</td><td colspan="3">Climate change mitigation and adaptation actions definition</td></tr>
<tr><td colspan="3">Land occupation (lowlands and river banks) for farming</td></tr>
<tr><td colspan="3">Massive clearance of forest for agriculture</td></tr>
<tr><td colspan="3">Artisanal gold mining in river courses</td></tr>
</table>

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Table 5 - Summary table of demo site context, Niger basin in Nigeria

NIGER RIVER BASIN inNigeria			
GENERAL CONTEXT	Distribution	36 states and 1 Federal Capital Territory, all divided into 774 Local Government Areas	
	Population	232.7 million (2024) [9]	
	Population density	255 (people per sq. km) (2024) [9]	
	Total GDP	252.74 billion of USD [10]	
	GDP per capita	1.11 thousand USD per capita in 2024 [10]	
ENERGY CONTEXT	Installed capacity	Total installed capacity 13.25 GW, mainly gas-fired plants and hydropower [24]	
	Share of renewables	Only 11.99%, mainly Hydropower (2021) [24], The goal is to reach 36% by 2030	
	Energy access	59.5% (2021), rate in urban areas reach 89.2% while rural areas just 23% [24] The goal is 90% by 2030.	
	Renewable energy potential	Solar radiation	5,535 kWh/m^2/day. 28 MW installed in 2019
		Hydropower potential	2.2 GW installed in 2021, but the total potential is around 14 GW
		Wind energy	10 MW (not yet commissioned in 2021)
	Most energy-intensive sectors	In 2021, the most consuming sectors were residential (around 60,000 TJ), followed by commercial and services (27,000 TJ) and industrial (14000 TJ)	
	Most pollutant sectors	Agriculture (AFOLU) is the biggest pollutant followed by energy industry, waste and road transport	
NATIONAL GOALS	90% electricity access by 2030		
	36% renewable energy by 2030		
	According to the NDC, 20% unconditional and 45% conditional emission reduction below Business as Usual (BAU) by 2030		
	30 GW installed on-grid capacity by 2030 with grid-connected renewable energy contributing 13.8 GW with the inclusion of medium and large hydropower, and 9.1 GW without them		
MAIN CHALLENGES	Climate change mitigation and adaptation actions definition		
	Land occupation (lowlands and river banks) for farming		
	Massive clearance of forest for agriculture		
	Artisanal gold mining in river courses		
	Water losses in the Inland Delta and escalation of losses due to other constructions		

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3. Analysis of existing energy-related models and databases

Starting with the understanding and relevance of energy models in the sub Saharan Africa, this section gives a review and analysis of existing energy-related models and databases in the AU region and more specifically in the Niger river Basin. The section gives an overview of the existing energy models and data base references, and the possible potential synergies, the weaknesses and the challenges for sustainable energy models data base.

Energy models can be classified into three main types, depending on how they process information: white-box, black-box and grey-box. This classification is used in general by data scientists, and is not exclusive for energy models. This model is based on physics and the properties of the system.

3.1. Overview Analysis of the existing energy related models and databases

Appropriate energy system models are essential for planning because they can be used to explore future energy demand and supply trajectories, incorporating projections of population, economic growth, and energy prices. Crucially, models can provide insights into how different policy and technological pathways could influence outcomes including environmental sustainability and economic development. These models are often used by policymakers to make decisions about infrastructure development, investment, and trade-offs.

About 77% of the 770 million people living without access to electricity today reside in sub-Saharan Africa (SSA). Increasing access to energy in the region could raise prospects for the 431 million residents there who live in poverty, while also advancing global climate goals. But the process of electrification has been hobbled by lack of data and one-size-fits-all energy system models that do not adequately reflect SSA's reality. Global institutions, as well as African governments, must begin to invest in the creation of national and regional energy models, data collection, and local expertise.

Most of the energy models applied to Africa are built and run by analysts in industrialized countries. As a result, the input of African analysts and local data can be limited, which results in poorly informed assumptions.

For example, in 2015, the International Energy Agency (IEA) energy balance showed that Nigeria's household electricity consumption was 14 TWh. However, using Nigeria-specific data, a bottom-up energy modelling study conducted by Nigerian analysts in collaboration with the International Renewable Energy Agency (IRENA) showed that Nigeria's household electricity consumption in 2015 was 43 TWh. The estimate tripled because the IEA didn't adequately capture how many households had diesel and gasoline generators to back up the unreliable grid. Energy models contain many implicit assumptions, such as those related to gross domestic product (GDP), which are often biased toward the expectations and priorities of industrialized countries, making them inappropriate for the SSA context.

Consequently, bringing expertise, data, and model development "home" to African countries is interrelated and mutually reinforcing with achieving electrification, development, and climate goals on the continent.

The *Table 6* below gives some open-source existing energy databases and models in Africa.

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Table 6 - Existing energy databases and models in Africa

Models	Data	Temporal Extension	Source
Energy	Nigeria Electricity Planning Model	2022	ESMAP [35]
	Report on Nigeria's Oil & Gas Sector	2021	Nigeria Oils and Gases [36]
	Existing approaches to modelling African energy transitions	2022	Elsevier publications [37]
	Nigeria vision 30-30-30	2016	Federal Ministry of Petroleum [38]
	Energy supply–demand models	2022	Elsevier publications [39]
	Emission reduction models	2022	Science direct [39]
	Forecasting models	2022	Science direct [39]
	Energy substitution models: On the interaction between energy and society	2021	Science direct [40]
	Energy-extended conceptual model	2023	ONEPlanET [41]
	Development and Demonstration of a Sustainable Open Access AU-EU Ecosystem for Energy System Modelling	2023	OASES [42]
Water Energy Food	WEF nexus in the Bani River Basin	2023	ONEPlanET [41]

3.2. Ongoing Projects

This subsection introduces ongoing projects with similar goals and pilot sites that could create potential synergies with the development of the EMERGE project. The possible connections between these projects will be further explored in *Task 6.2. Networking and connection to other activities*. This analysis will include projects such as ONEPlanET, D4D Hub, LEAP-RE and EMERGE's "Sister projects".

In European initiatives, a "sister project" refers to a set of projects funded by the European Union (EU) that share similar goals, thematic areas, or objectives, and are designed to complement each other. These projects typically collaborate, exchange knowledge, and build synergies to enhance their collective impact. Sister projects often focus on different aspects of a broader topic, such as a clean energy transition; allowing them to tackle a common challenge from multiple perspectives. In this case EMERGE's Sister projects are RE-INTEGRATE and OpenMod4Africa; which will be defined below.

3.2.1. ONEPlanET

The design of the ONEPlanET [43] energy model consists of three main conceptual parts: the final energy demand of the non-energy productive sectors and households, the final energy generation and the energy balance, where supply and demand are compared. Since it is a model designed at the local scale, it is considered that the energy deficit (final energy demand > final energy generation) results in energy imports, and the same would be true for exports in the case of surplus of energy generation. This methodology considered a distinction between "energy isolated population" (generally rural areas) and "energy interconnected population" (generally urban areas connected to the grid). For both cases, a different energy solution is proposed to cover the energy shortfalls, including grid expansion for new connections, and installation of microgrids or stand-alone systems.

The energy sector includes a mix of renewable and non-renewable generation technologies, such as: photovoltaic power plants, hydropower, onshore wind, biomass, coal-fired and gas power plants.

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3.2.2. D4D Hub

The D4D Hub (Digital for Development Hub) [44] is a European initiative aimed at fostering sustainable digital transformation through collaboration between the European Union and other regions; including Sub-Saharan Africa (SSA). It seeks to build digital infrastructure, enhance skills, and improve public services by leveraging technology and innovation. The initiative prioritizes inclusivity and sustainability, ensuring that digital growth contributes to overall development goals, particularly in energy, education, and governance sectors.

3.2.3. LEAP-RE

The LEAP-RE (Long-Term Joint EU-AU Research and Innovation Partnership on Renewable Energy) project [45] is a collaborative initiative between the European Union and the African Union aimed at accelerating renewable energy adoption through research and innovation. Its main objective is to develop sustainable energy models that support economic growth and environmental protection. The LEAP-RE portfolio focuses on six priority themes, including smart-grid and off-grid systems, geothermal energy, productive and domestic uses, and access to energy. These efforts encompass 31 renewable energy research and innovation projects, involving 83 African and European partners across various sectors. Pilot sites are located in countries such as Mozambique, Morocco, South Africa, and Kenya.

3.2.4. RE-INTEGRATE

RE-INTEGRATE [7] is an EU-funded project that aims to analyse and improve the energy planning system within and between the African Union and the European Union. It sets out its objectives and principles in three key pillars:

a) exchanging and sharing knowledge on energy planning

b) providing expertise on developing an integrated 3E modelling (energy-economy-environment) aligned with a sustainable energy development that helps policy-makers take informed decisions

c) creating modelling toolkits tailored to the specific case studies (8 national cases: Tunisia, Ethiopia, Kenya, Mauritius, Zambia, South Africa, DRC, Senegal).

The models used in the framework of this project include OSeMOSYS (with versions adapted to each country) and FlexTool.

3.2.5. OpenMod4Africa

OpenMod4Africa [6] focuses on collecting state-of-the-art energy models in an open toolkit with the objective of analysing decarbonisation pathways that ensure a secure and competitive energy ecosystem in Africa. This project is committed to delivering open models with scalability and applicability at different levels such as cities, countries or industries, providing free access to academia, industry and policy-makers, who will be able to exploit it and achieve a clean energy transition.

3.3. Conclusions

- Case studies in Nigeria demonstrate that for electrification projects to create meaningful increases in income, they need to consider a community's ability to pay electricity bills, as well as its credit availability and market development. However, few energy models explicitly capture this process, thus creating unrealistic projections for Africa's future energy demand. For the Bani River Basin, located in Mali, the search for relevant WEF Nexus policies and targets has been quite arduous, as despite the existence of several policies related to the topic, most

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of them do not provide any target value to achieve. Thus, all these inputs cannot be used for the quantitative creation of the scenario.

- The economic metrics used in African countries' energy models require attention to local knowledge and geography. Energy models in industrialized countries use GDP and per capita GDP as driving factors for energy demand. However, in African countries the usual methods of calculating GDP frequently underestimate true economic activity, especially where informal employment is common.
- The International Labour Organization estimates that 85% of employment in Sub Sahara Africa (SSA) is informal. For instance, when Nigeria rebased its GDP to include some informal sectors, that measure increased by over 60%, from $270 billion to $510 billion, revealing that Nigeria's economy was larger than that of South Africa's. This implies that models relying on GDP to forecast Nigeria's energy demand before 2014 could have underestimated the country's energy needs, leading to inadequate energy plans.
- Another challenge in applying global energy system models to Africa is spatial representation. Today, the 54 sovereign countries in Africa have natural resources, systems of government, and levels of foreign dependency that vary widely. Despite these differences, energy models tend to aggregate African countries into a single region—occasionally with the Middle East—or into several regions. For example, in the Integrated Model to Assess the Global Environment (IMAGE), Africa is represented as five regions: Northern Africa, Western Africa, Eastern Africa, South Africa, and Rest of Southern Africa.
- Lack of country-specific models also hampers planning for changing balances between rural and urban populations and proximity to grid-based power. In some SSA countries, particularly those with lower levels of electricity access, off-grid solutions such as solar home systems, mini-grids, and solar lanterns have helped to improve energy access at the subsistence level. However, many households, given the opportunity, would prefer to be grid-connected because its electricity is cheaper and more reliable and can potentially support larger equipment. With an appropriate local integrated electrification planning framework, decisionmakers could plan for a convergence of off-grid and on-grid services as the grid grows and populations shift. At local and national levels, deployments of off-grid, decentralized, renewable energy systems affect present and future power demand on the grid.
- Despite the above facts, most of the existing energy system modelling studies and plans do not have a comprehensive strategy for grid convergence.
- Inability to model market behaviours has prevented many countries in Africa from meeting their objectives. The Nigeria's Vision 30:30:30, for example, which aims to achieve 30 gigawatts of generation by 2030, with renewable energy contributing 30% of the energy mix, is far behind its targets. As of 2022, the country still had not met the benchmarks for 2017.
- Currently, there are few Africans in the energy modelling space. Many of the research work is produced without an author based on the African continent. National governments in Africa must build a pool of local experts for their own countries by facilitating partnerships between local academic institutions in Africa and relevant experts from developed countries.
- Finally, there is also a need for existing African institutions involved in energy modelling and planning to pursue partnerships with various international institutions—establishing regional dialogues, facilitating the exchange of technical advice, and assisting African researchers to learn from best practices in energy modelling globally.

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4. Common System Architecture (CSA) for Energy System Models

The EMERGE project aims to provide African policymakers, academics, investors, and citizens with the necessary tools and knowledge to increase clean energy production and promote sustainable development, while addressing social, climatic, economic, and technical challenges. To achieve this goal, a Common System Architecture (CSA) will be defined to serve as a comprehensive framework to integrate African-specific parameters (economic, social, environmental, and technical) into the EMERGE Toolbox as shown in *Figure 1*.

The list of African-specific parameters will come from the definition of the EMERGE Use Cases on the project's deliverable D5.1 - Pilot and Use Cases definition [8] and from the WP1 *EMERGE Knowledge Base;* to be integrated on the EMERGE Toolbox and Database ensuring to provide tailored solutions adapted to African needs. One example would be to include cooking and not be focused only on the main electric sector; since cooking is still considered a major problem of health and pollution in south-east Africa due to the use of fossil fuels as coal. More needs will be identified through the collaboration of partners and stakeholders on WP1 and WP4 to constitute a "Knowledge base" which will be integrated into the database as part of subtask *T2.4 Implementation and running of the EMERGE Knowledge Base;* these results will be prepared for next version of this deliverable D2.2 Database due for M24 (November 2025).

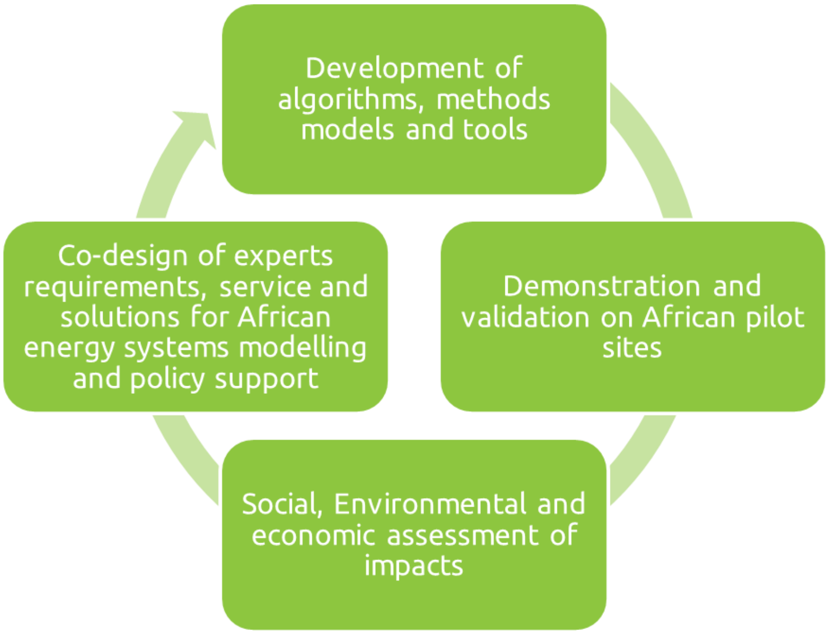

Figure 4 - CSA iterative methodology steps

The process of defining the CSA will follow a structured, iterative methodology; encompassing co-design, development, piloting, and assessment, as shown in the *Figure 4*. Following this methodology will ensure that the architecture will be designed to be flexible, interoperable, and replicable; also enabling the integration of various energy vectors such as electricity, water, and transport.

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In the following chapters there is an overview of the process followed for the preliminary definition of the CSA, where main steps have been included on *Figure 5.*

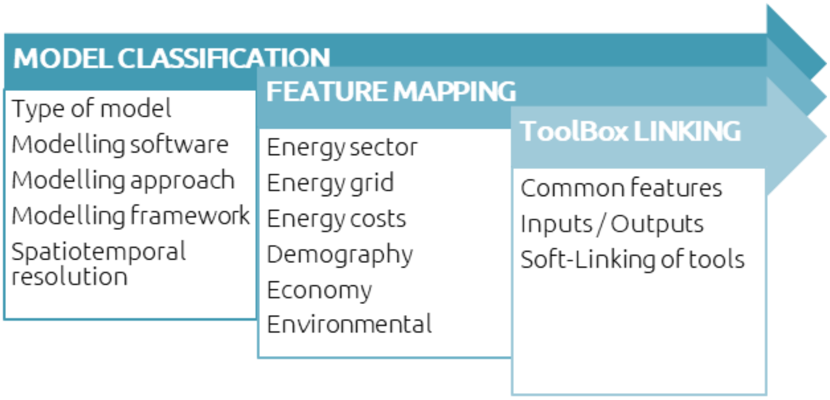

Figure 5 - CSA followed methodology

- The first subchapter 4.1 will introduce the project tools and the literature review process conducted to analyse different open-source energy models, and the evaluation criteria followed for its classification. Then, subsequent sections will delve into the evaluation of model functionalities, known as features; to identify synergies between the different models.
- Additionally in subchapter 4.2, a more detailed analysis will be carried out for the EMERGE project tools or Toolbox, setting the base for the identification of possible interlinkages between them, following a soft-linking approach [46] connecting outputs from one tool as input for another.

4.1. Model classification and evaluation of features

Building a Common System Architecture (CSA) requires the analysis and understanding of the characteristics of the project's tools that will form the EMERGE Toolbox, not only in terms of modelling features, but also in other terms such as temporal and geographical granularity, mathematical method or simulation approach. The list of project tools main description and challenge to address is given in the *Table 7* below:

Table 7 - EMERGE tools description

EMERGE tools description
Hosting capacity The Hosting Capacity tool, currently under development, its primary objective is to support electric system planning, with a focus on integrating new generation capacities and loads. Additionally, efforts are directed towards optimizing the resilience and sustainability of the electric system, specifically through improved generation expansion planning, dynamic contingency analysis, and achieving optimal economic and environmental outcomes. Developed by CIRCE CHALLENGE Diagnosing the points in the electric system where new renewable generation plants can be installed, points with sufficient transport capacity to evacuate the energy from these new generation plants.

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EMERGE tools description	
Optimal Storage Placement	The Optimal Storage Placement tool is being developed using open-source software and aims to identify points in the grid where the integration of batteries can improve the system's key variables of interest.

This involves identifying strategic locations to optimize the performance and efficiency of the system using energy storage solutions. Additionally, a visualization dashboard is being designed to provide a clear and comprehensive representation of potential improvements in key system variables such as grid stability, energy efficiency, and operational cost.
Developed by CIRCE

CHALLENGE
Diagnosing the points in the electric system where battery energy storage systems (BESS) can be installed, points with sufficient transport capacity to evacuate the energy from these new installations.

GREENADVISE	GREENADVISE, currently under development, is an investment advisor based on a Python module and used for the optimization of small-scale energy systems on a community or small city scale.

Its' application can range from household or building level to small city and is suitable for citizens as friendly investment advisor with educational material for raising awareness about benefits of clean energy transition of AU.
Developed by UNIZAG

CHALLENGE
GREENADVISE finds optimal renewable capacities for the modelled system, develops hourly optimized system operation, and finds economically optimal solutions.

CEPIA	CEPIA is an excel-based tool allowing for user-friendly assessment of energy and climate scenarios through multiple economic and environmental indicators.

The tool is entirely based on a library of possible levers and the assessment of their environmental impacts and costs.
It allows users to forecast the effect of the levers on the different economic and energy sectors, enabling the evaluation of the different impacts and the definition of operational goals (e.g. switch to LPG stove for cooking, increased penetration of renewables in the power grid, changes in the modal shares for means of transport, etc).
Developed by Artelys

CHALLENGE
This tool is to be used mainly by energy modellers and output parameters will help policy-makers in designing policies to support specific scenarios obtained with the tool

PowSyBl - METRIX	PowSyBl is an open-source framework currently used by European TSOs for electrical grid modelling and simulation (power flow computation, security analysis, sensitivity analysis, time domain simulation).

Part of the overall software is the METRIX framework which is dedicated to power network flows calculations with an hourly timestep resolution.
Developed by Artelys

CHALLENGE
In this project, the focus will be on including the modelling of flexibility solutions for the network (such as battery storage) in the METRIX framework. This will enable running simulations to minimize curtailment of renewables and/or help in assessing the hosting capacity of renewables in a grid.
The addition of such a tool in EMERGE will help complement and validate outputs of energy planning tools (e.g. CEPIA tool)

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4.1.1. Model classification

For the analysis of these tools, and with the aim of broadening the scope of the study, a literature review process was conducted including other similar and useful tools and models beyond it. The steps and evaluation parameters for the literature review have been defined based on different references like ONEPlanET deliverable *D2.1 - Report on the selection of functions and functionalities from previous models* [5], consisting of the following steps:

- First, a model screening process was conducted to identify and select similar open-source models, followed by an analysis of their scope and definition on *Table* 8.
- Afterwards, a more detailed analysis was conducted to identify and group the different capabilities or features for each model, as shown in the *Feature mapping* in *Table 11*.

During the model screening process websites like *The Energy Modelling Platform for Africa* [47] were visited with the aim to locate open-source models adapted to the pilot sites context like OSEMOSYS in Morocco [48], ONSSET on Nigeria [49] and LEAP or MOZLEAP in Mozambique [50]. More details on these models are gathered in *Table* 8 below.

Thus, based on some studies of reference such as [51] and [52], it is possible to establish several parameters to define and classify models and tools as described below:

Type of model (IAM/Non-IAM):

An Integrated Assessment Model (IAM) is a tool used to explore the interactions among the economic, energy and climate systems by combining information derived from economy, engineering, policy, etc. These models aim to assess long-term consequences of environmental policies on variables like global temperature, GHG emissions or GDP growth [53]. Therefore, the analysed tools may include various different interconnected modules (IAM approach) or only the energy sector; closer to Energy System Models (ESMs).

Modelling software:

It refers to the programming language and development environments employed to build and simulate the tools and analyse their outputs. The same tool can be adapted to different coding languages to ease its dissemination. Some of the most popular modelling software in this regard are Python, Java Script or C++.

Modelling approach:

A modelling approach refers to the methodology used to design and structure models or tools that analyse complex systems across key areas such as economics, energy, and the environment. These models serve to aggregate and process essential information to simulate and understand the dynamics of these systems. The three most relevant approaches are:

- **Top-Down (TD) models**: Focused on a macroeconomic level and long-term changes with an “economic approach”, simulates and analyses the relationships between different sectors (energy, economic, environmental and social) at a national or regional level. These TD models can evaluate the effects of different energy and climate policies or even or market mechanisms (e.g. carbon taxes) to evaluate the effect on the other sectors as GHG emissions, economic growth, job creation, welfare, etc.

- **Bottom-Up (BU) models**: Focused on a microeconomic level with an “engineering approach”, provides detailed technological insights into supply and demand. These models simulate and optimise energy systems using their specific equations and properties. BU models accounts for challenges like current energy supply and electrification level, variability of renewable energy

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sources, performance of end-use technologies; aiming to identify the least-cost option of supply and demand.

- **Hybrid models**: Integrates both Top-Down and Bottom-Up approaches, considering the overall macroeconomic perspective and including more details on the technological level.

Modelling framework:

Depending on the objective the models use their specific equations for, their framework can be categorised as:

- **Simulation framework**: These are complex tools that mimic how energy systems (like power plants, grids, and consumers) behave under different scenarios, helping to understand potential future outcomes, i.e. "*provide a detailed picture of system reactions*".

- **Optimisation framework**: They provide the optimal configuration for the energy system by minimizing the cost of supplying a certain exogenous demand, considering the constraints related to the available technologies and their technical and economic aspects, i.e. "*the most effective strategies for system setup and operation*".

Spatiotemporal coverage and resolution:

Besides the methods used to build and make the model functional, it is also indispensable to pay attention to the temporal and geographical granularity that the tools can provide. Here, it is possible to differentiate between coverage or horizon and resolution:

- **Coverage**: The furthest time a model can cover, i.e. the operational horizon over which a model runs, covering the short to mid and long terms. The tools of interest usually work with long-term horizons, around 20 to 50 years. Coverage must also be geographically addressed, spanning from local to regional, national, continental and global levels.

- **Resolution**: This concept refers to the time step a tool uses to work and to provide results. Thus, temporal resolutions can be adjusted from years to hours.

In summary, a total of 14 tools were defined and classified during the model review to identify the most relevant and common features, including all five project's tools (defined on Table 7), plus nine additional tools selected during the model screening process. Main findings from that analysis are represented on:

- *Table 8* presents a more general classification, using the aforementioned groupings and also the type of licence (i.e. open source or private) and the online link where the tool can be found.
- *Table 9* includes additional energy vectors and end-use sectors (demand sources) considered for the internal calculations, e.g. electricity, diesel, agriculture, transport, etc.

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Table 8 - Model Classification

Model Classification										
Tool/Model	Full-name	IAM/Non-IAM	Software	Model Approach	Modelling Framework	Temporal Resolution	Temporal Coverage	Geographical Coverage	Source Link	License
Hosting Capacity	Hosting Capacity	Non-IAM	Python	Bottom-up	Optimisation	Hourly	Long-term	Flexible, depending on specificities	https://github.com/SanPen/GridCa	Open Source
Optimal Storage Placement	Optimal Storage Placement	Non-IAM	Python	Bottom-up	Optimisation	Hourly	Long-term	Flexible, depending on specificities	https://github.com/SanPen/GridCa	Open Source
GREENADVISE	GREENADVISE	Non-IAM	Python	Bottom-up	Optimisation	Sub-hourly (adjustable to lower)	One to several years	From global to local	Not available yet	Open Source[1]
CEPIA	Climate and Energy Prospective Impact Assessment Tool	IAM	Excel	Bottom-up	Simulation	Five-year	Up to 2050	National	Not available yet	Open Source
PowSyBl - METRIX	Power System Blocks - METRIX	Non-IAM	Java, C++	Bottom-up	Optimisation	Hourly	Up to a few years	Flexible, depending on specificities	https://github.com/powsybl/powsybl-metrix	Open Source
OSeMOSYS	Open Source Energy Modelling System	Non-IAM (Framework)	Python GAMS GNUMathprog	Hybrid	Optimisation	Hourly (adjustable to lower)	Up to 2100	National, but adjustable	http://github.com/OSeMOSYS/OSeMOSYS	Open Source[2]
FlexTool	IRENA Flexible Tool	Non-IAM (Framework)	GNU MathProg	Bottom-up	Optimisation	Hourly (adjustable to lower)	Up to 30 years	From global to local	https://irena-flextool.github.io/flextool/	Open Source
OnSSET	Open-Source Spatial Electrification Tool	Non-IAM (Framework)	Python	Bottom-up	Optimisation	Yearly	Up to 2030	From global to local (+ 10 available areas)	https://github.com/KTH-dESA/OnSSET-2016	Open Source
CLEWs	Climate, Land-use, Energy and Water systems	Non-IAM (Framework)	Python Java Ruby Perl	Bottom-up	Simulation	Monthly - Yearly	-	From global to urban	https://github.com/OSeMOSYS/CLEWs	Open Source
EAE	Energy Access Explorer	Non-IAM (online platform)	Java		Optimisation	Yearly	-	From national to local	https://github.com/energyaccessexplorer	Open Source[3]
MicroGridsPy	MicroGridsPy	Non-IAM	Python	Bottom-up	Optimisation	Hourly	Long-term	Local (remote villages)	https://github.com/SESAM-	Open Source

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Model Classification										
Tool/Model	Full-name	IAM/Non-IAM	Software	Model Approach	Modelling Framework	Temporal Resolution	Temporal Coverage	Geographical Coverage	Source Link	License
									Polimi/MicroGridsPy-SESAM	
RAMP	Remote-Areas Multi-energy systems load Profiles	Non-IAM (Framework)	Python	Bottom-up	Simulation	Hourly	Flexible	Local	https://github.com/RAMP-project	Open Source
MOZLEAP	Mozambique – Long range Energy Alternatives Planning System	IAM	Visual Basic	Bottom-up	Simulation	Yearly	Up to 2030	National	https://mpra.ub.uni-muenchen.de/65967/	Open Source[4]
ETM	Energy Transition Model	Non-IAM	Ruby	Bottom-up	Simulation	Yearly	Up to 2050	National Regional Local[5]	https://github.com/quintel/documentation	Open Source

[1]It uses GUROBI which is free only for academic users
[2]Except GAMS version
[3]MIT license
[4]Licenses are free for academic, governmental and non-profit organizations based in a developing country
[5]Regionally and locally only for some regions in The Netherlands

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Table 9 - Classification of the models based on their main properties

		Hosting Capacity	Optimal Storage Placement	GREENADVISE	CEPIA	PowSyBl - METRIX	OSeMOSYS	FlexTool	OnSSET	CLEWs	EAE	MicroGridsPy	RAMP	MOZLEAP	ETM
Modelling Approach	Bottom-Up	■	■	■	■	■		■	■	■		■	■	■	■
	Top-Down														
	Hybrid						■								
Type of model	IAM				■									■	
	ESM or others	■	■	■		■	■	■	■	■	■	■	■		■
Modelling Framework	Simulation				■					■			■	■	■
	Optimisation	■	■	■		■	■	■	■		■	■			
	Both														
Temporal Resolution	Hourly	■	■			■						■	■		
	Monthly														
	Yearly								■		■			■	■
	> Yearly				■										
	Flexible			■			■	■		■					
Temporal Coverage	Short-term														
	Mid-term			■		■			■						
	Long-term	■	■		■		■	■	■			■		■	■
	Flexible												■		
Geographical Coverage	Local											■	■		
	Regional														
	National				■		■							■	
	Global														
	Flexible	■	■	■		■		■	■	■	■				■
Energy Vector	Electricity	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Gas				■			■	■	■	■	■		■	■
	Heat				■			■	■	■			■	■	■
	Diesel				■			■	■	■			■	■	■
Sector / End-use	Mobility				■			■	■	■			■	■	■
	Industry				■			■	■	■			■	■	■
	Residential				■			■	■	■			■	■	■
	Agriculture				■		■	■		■			■	■	■

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4.1.2. Model feature mapping

The identification of features within the models is necessary to determine which ones are to be included on the EMERGE Toolbox; considering both the most common identified features and the more specific ones related to the use cases definition; resulting in a comprehensive yet concrete tool, that can be adapted to the African context. The different main feature groupings are defined in *Table 10* below.

Based on ONEPlanET deliverable D2.1 [5], a feature can be defined as *"each of the specific characteristics that a model incorporates, i.e. each attribute of the system that is represented in the model. These features are the basic unit of System dynamic Models (SDMs) and are usually the output that the user receives when using the model. A feature can be understood as the result of the interaction between constants and variables by means of mathematical relations, with a changing value over time according to the inputs, and which can serve as input for other features of the model itself."*

Table 10 - Feature categories definition

FEATURE CATEGORIES DEFINITION	
Energy Access	Percentage of the population with access to electricity known as electrification, as well as technical properties of the main power grid that defines their reliability like the properties of its components, topology and total imported energy.
Energy Demand	Energy Demand [TJ] can be disaggregated by sector if there is available data; it can be measured in primary and/or final energy. As well as more detail on the final consumption side with data like hourly consumption profiles, demand per capita, power flow calculated as a balance between imported-exported and stored energy.
Energy Supply	Energy Supply [TJ] includes variables as total energy production, hourly generation profile and current installed capacity in [MW]. Energy supply can be also disaggregated by energy vector (heat and electricity), by sector and by technology if there is data available.
RES availability	Renewable Energy Sources (RES) availability expressed the amount of energy that can be harnessed from natural resources like hydro, wind, solar and biofuel
Energy costs	Energy costs of energy production, supply and final user prices for energy and fuels.
Water Availability	Water Availability can be calculated as a fraction between demand and supply, [m^3], it can be calculated for groundwater and surface water volumes. It can be disaggregated by sector if there is available data, or estimated based on other parameters.
Land Use	This includes data on the net available land, and especially for renewable energy sources, for biomass generation or for other RES plants installation (solar, hydro…)
Demography	Demography includes population data and future growth trends, this can be affected by variables like migrations, age structure or population density and urbanisation trends.
Economy	Includes variables like GDP, GDP growth and GDP per capita. This can be affected by variables like taxes, investments or sectoral structure.
Environmental	Climate change impacts, like GHG emissions (CO_2, CH_4) and other emissions (NO_x).
Electricity Grid	Technical parameters of the electrical grid network including the properties of generators, load, shunt, branch and transformers. Including Active power measured in [MW], reactive power [MVA] and voltage [kV].

In this subsection, all the models previously defined and classified on *Table* 8 and *Table 9* have been thoroughly analysed to identify features aligned with the pilot sites and tools objectives, with the goal of establishing a well-rounded model. To facilitate the clarity and understanding of the results, the selected features have been refined, cleaned and grouped to ensure consistency across different models (e.g. harmonizing features with different names).

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Table 11- Feature mapping of tools and models

Class	Energy Access					Energy Demand									Energy Supply									Energy costs			
Feature	Energy Import	Power grid reliability	Electrification	Network properties	Topology of the network	Total energy demand	Energy demand per sector	Primary energy demand	Final Energy Demand	Consumption profile	Energy demand per capita	Imports / exports and storage	Net imported energy	Net exported energy	Energy Production	Generation profile	Elec. generation mix	Heat Generation	Elec. generation capacity	Heat generation capacity	Energy losses	RES Availability	Energy intensity	Energy production cost	Energy Supply Costs	Fuel price	Energy Price
OSeMOSYS																											
FlexTool																											
OnSSET																											
CLEWs																											
EAE																											
MicroGridsPy																											
RAMP																											
CEPIA																											
Hosting Capacity																											
Optimal Storage Placement																											
GREENADVISE																											
PowSyBl - METRIX																											

Class	Water Availability					Land Use			Demography		Economy			Environmental		
Feature	Ground-water	Surface water	Water Reservoirs	Water demand (per sector)	Water demand (energy sector)	Net available land	Land for RES (solar, hydro, wind)	Land for RES (biomass, biofuel)	Population	Annual growth rate	GDP (per capita)	GDP growth rate	Income per capita	Climate Change impacts	GHG emissions	Other emissions
OSeMOSYS																
FlexTool																
OnSSET																
CLEWs																
EAE																
MicroGridsPy																
RAMP																
CEPIA																
Hosting Capacity																
Optimal Storage Placement																
GREENADVISE																
PowSyBl - METRIX																

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4.2. EMERGE Toolbox soft-linking

In this subchapter will identify potential synergies between the different components of the EMERGE Toolbox, based on linking techniques for models [46]. There are two main groups of linking techniques:

- Soft-linking

This approach consists of connecting the outputs from one model as input for another one.

Soft-linking offers more flexibility and adaptability across models with different structures or spatial and time resolutions. This method is less computationally intensive and mitigates error propagation but may result in inconsistent outcomes. Additionally, it requires ongoing maintenance as models are updated or modified, and does not guarantee simultaneous convergence between models.

- Hard-linking

This approach consists of a deeper integration between the underlying mathematical formulations of the models involved, resulting in a more robust and efficient approach for exchanging data between models, offering stronger convergence criteria, avoiding interactive processes.

However, this method results more computationally intensive and time-consuming, and can even create a “black box” effect, where the interactions are unclear and it becomes difficult to interpret how the information is transferred.

The main challenges in both linking strategies include identifying and defining common inputs, features, and convergence solutions. In soft-linking, this challenge is compounded by the need for harmonization across models, while hard-linking requires more detailed mathematical integration. In either case, it is essential to harmonize assumptions, methodologies, units, and resolutions across models.

For energy system models (ESMs), it is crucial that all components operate within a common economic, technical, social, and environmental framework, such as the CSA framework, to ensure effective model integration and consistent results.

In this case, the *soft-linking approach* was chosen due to its flexibility and the ease of tracking interactions between tools. This approach also aligns with other European initiatives, such as ENCLUDE project, where they developed a similar framework as a “*Modelling ensemble process*” for different energy models as explained on their deliverable D5.1 [54].

The "*Modelling Ensemble Process*" is a soft-linking technique for models, where the process begins by identifying the inputs and outputs of each model, ensuring their alignment in terms of scale, units, and analysis methods. Assessing the consistency of inputs and outputs is a crucial step to ensure that data from different models can be effectively combined into a cohesive system; or if any adjustments or aggregation/disaggregation is necessary. Then, defining the order of execution for linking models is equally important, as it facilitates the smooth integration of data across multiple tools.

This subchapter includes the identified common features or synergies between project tools (defined the *Table 7)* as shown in *Table 12*. Plus, a detailed schema of inputs and outputs of each tool on *Figure 6*; from this mapping of inputs/outputs, possible soft-linking connections have been identified and represented on the figures: *Figure 7, Figure 8, Figure 9, Figure 10,* and *Figure 11.*

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At this stage, the identified interlinkages are preliminary and aggregated under the feature definition, to make the diagrams easier to understand. As the project continues, further refinement of links and connections will take place, and more detailed results will be provided on future deliverables such as D2.2 EMERGE Database, due for November 2025.

Table 12 - Feature synergies between EMERGE tools

Tool / Feature	Hosting Capacity	Optimal Storage Placement	GREENAD VISE	CEPIA	PowSyBI - METRIX
Electricity system reliability					
Electricity generation technology mix					
Electricity generation capacity					
Total national energy demand					
Net imported energy					
Energy Production					
Energy demand per sector					
Topology of the network					
Generation profile					
Consumption profile					
Energy import, export and storage					
Net exported energy					
Energy production cost					
Energy Supply Costs					
Energy Import					
Final Energy Demand					
Energy demand per capita					
Energy losses					
Net available land					
Greenhouse gas emission					
Other emissions					
Electrification					
Primary energy demand					
Heat Generation					
Heat generation capacity					
RES Availability					
Energy intensity per source					
Fuel price					
Energy Price					
Population (per age range)					
Average annual growth rate					
GDP					
GDP per capita					
GDP growth rate					

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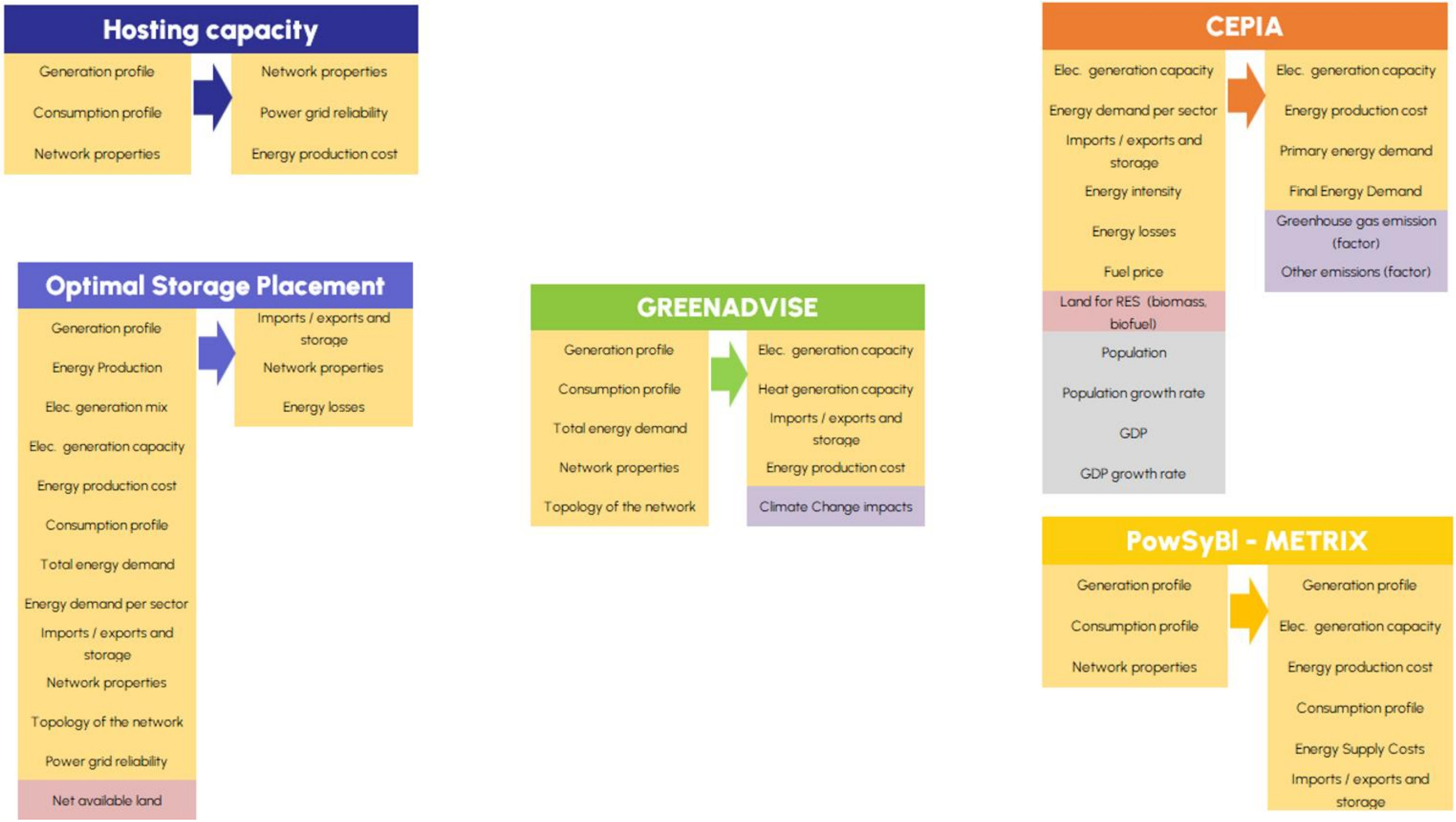

Figure 6 - Feature mapping of inputs and output of EMERGE tools

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This chapter outlines the methodology, which followed a series of steps. First, *Table 12* presents the main synergies identified between the EMERGE project tools (defined in *Table 7*), based on the previous feature analysis. Next, each project tool underwent a more detailed analysis to identify key inputs and outputs, which were then aggregated as features, as illustrated in *Figure 6* for easier data interpretation. Finally, soft-linking diagrams were developed to highlight potential interconnections and synergies between the tools, as shown in *(Figure 7, Figure 8, Figure 9, Figure 10* and *Figure 11).*

Main conclusions that can be obtained from the model classification table are listed below:

- The EMERGE Toolbox shares common properties across models, such as the use of Python as modelling language; or the ability to be adapted to Python.
- All project models are focused on energy system optimization; except for CEPIA that is an Integrated Assessment Model (IAM) for simulating future scenarios.
- All tools are open source, though some are still under development and lack full documentation, which will be provided in future deliverable versions.
- Model coverage is flexible for most tools, depending on scenario specifications and data availability, except for CEPIA, which operates at a national level.
- While most tools are primarily focused on the electrical grid, CEPIA integrates multiple energy vectors, like natural gas, heat, and other fuels; and covers a broader range of end-user demands, including residential, mobility, industry, and agriculture.

4.2.1. Hosting Capacity soft-linking

The ***Hosting Capacity tool*** developed by CIRCE (currently under development), is focused on the optimisation of the electric system, planning the integration of new generation capacities and loads to increase the network resilience and contributing to sustainability goals. The optimisation identifies points in the electric system where new renewable generation plants can be installed, accounting for dynamic contingency analysis, and achieving optimal economic and environmental outcomes.

Its main inputs are hourly generation and consumption profiles and the properties of the network elements like loads, transformers and static generators. Main outputs are the optimised power grid reliability and network properties, and optimised network resilience, as well as the optimal economic and environmental outcomes; these outputs can be connected to the following tools:

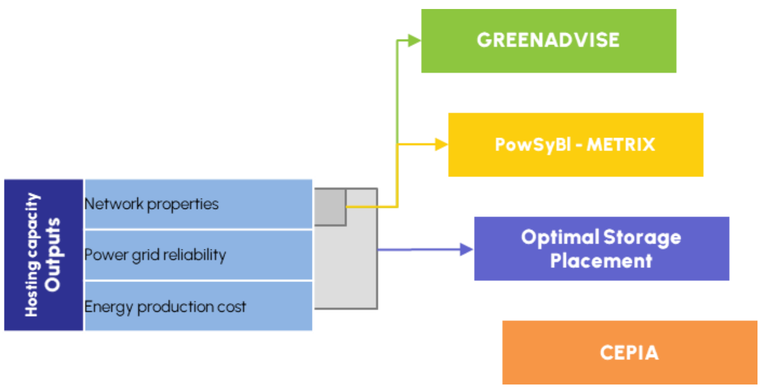

Figure 7 - Links between Hosting capacity and other EMERGE tools

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4.2.2. Optimal Storage Placement soft-linking

The *Optimal Storage Placement tool* developed by CIRCE (currently under development), similarly to the previous one is focused on the optimisation of the electric system, identifying the most strategic locations to optimize the performance and efficiency of the system with new battery electric storage system (BESS), focused on improving the resilience of the grid detecting overload issues on the electric lines.

Main inputs are hourly generation and consumption profiles, as well as network properties of loads, transformers and static generators among others. Main outputs are the optimised power grid reliability with new storage points, which can be measured as network properties like voltage and loading; it also includes optimal economic and environmental outcomes. The tool outputs can be connected to the following tools:

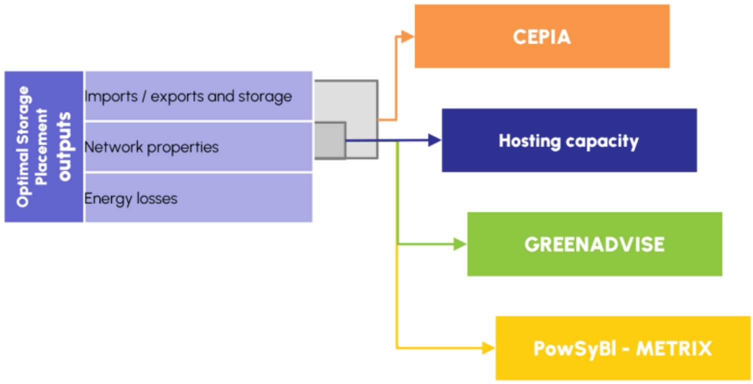

Figure 8 - Links between Optimal Storage Placement and other EMERGE tools

4.2.3. GREENADVISE soft-linking

The *GREENADVISE* investment advisor developed by UNIZAG (currently under development), is based on a Python module and can be used to find the most economically optimal renewable capacities to be installed on small-scale energy systems at community scale or small city scale.

GREENADVISE main inputs are hourly data as electric and thermal demand profiles, energy prices, renewable generation potential (solar, wind, biomass) and weather conditions. The outcome of this tool would be the optimised energy streams and generation and storage capacities to cover both electric and thermal loads, accounting for its financial and economic viability and impacts on the environment. These outcomes can be soft-linked as follows:

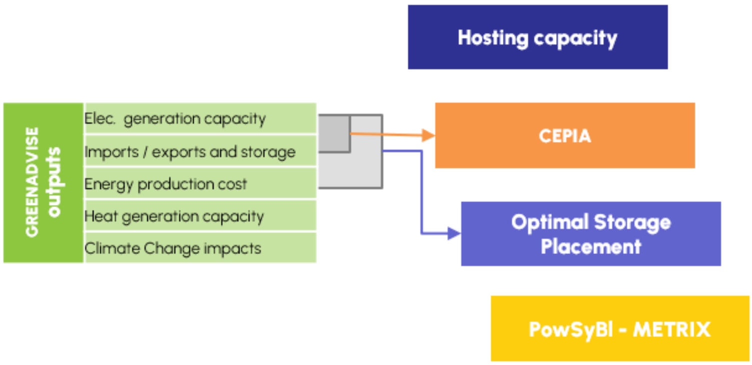

Figure 9 - Links between GREENADVISE and other EMERGE tools

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4.2.4. CEPIA soft-linking

The *Climate and Energy Prospective Impact Assessment Tool* or ***CEPIA tool*** is an excel-based tool developed by Artelys; which allows to assess energy and climate scenarios through multiple economic and environmental indicators. CEPIA tool has defined two different sets of inputs the first set defines the current context to build the demand, and the second group which are the variables of actions that can be modified to create the scenarios. All of the inputs are referred to five different demand sectors (residential commercial and services, industry, agriculture and transport), which can be divided or aggregated to match the other tools, and to adapt to data availability.

Main outcomes are the estimated demand per sector, the optimised generation capacity, production costs and the expected impacts on the environment; that can be used as inputs for the following tools:

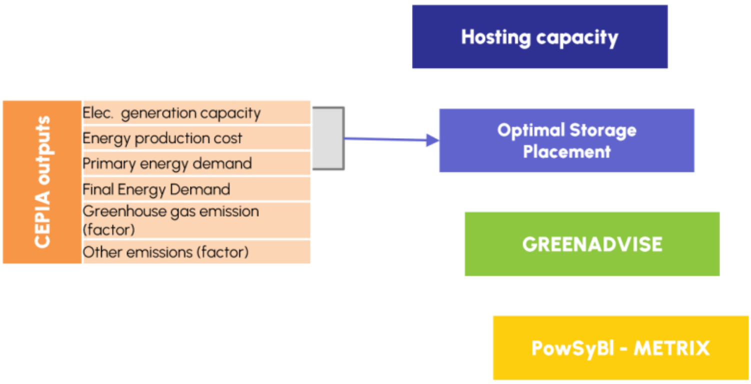

Figure 10 - Links between CEPIA and other EMERGE tools

4.2.5. PowSyBl-METRIX soft-linking

The ***Power System Blocks – METRIX*** tool developed by Artelys, is an open-source framework, used for power network flows calculations with hourly resolution, to increase the flexibility of the network minimising the minimize curtailment of renewable energy sources, through the definition of storage solutions, similar to the aim of *Optimal Storage Placement tool,* and validating the output of other tools like *CEPIA*.

Main inputs include the hourly generation and consumption profiles as well as grid topology and network properties; the expected outcomes are the power flow calculation on each element (imported/exported/stored energy), and the optimised generation and consumption profiles; and their impact on energy generation and supply costs. These outputs can be used as inputs for the following tools:

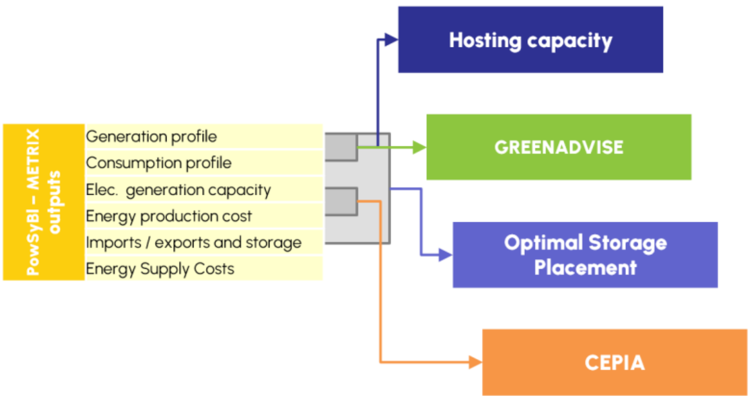

Figure 11- Links between PowSyBl – METRIX and other EMERGE tools

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In conclusion, the soft-linking diagrams highlight the potential interconnections between EMERGE project tools; however, these interlinkages remain preliminary and aggregated under the feature definitions. To enable effective integration between the tools and the database, a more detailed analysis is needed, focusing on the disaggregation on the individual units and calculation method for each individual element will have to be done.

This will ensure that data from different models can be seamlessly combined into a cohesive system, while identifying any necessary adjustments or aggregation/disaggregation required for proper alignment.

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5. Database schema

The development of a central database in this project is crucial for ensuring that all necessary data is accessible to the tools that rely on it for efficient operation. By providing a central storage, the database enables seamless integration between the various tools developed within the project and ensures future development with the existing infrastructure. The database design ensures that data is consistently available for analysis, forecasting, and optimization across a range of operations. Additionally, the database is flexible enough to support ongoing development, enabling adaptability for future updates and new features as the project evolves.

Functionality

The core functionality of the database is designed to store and manage a wide range of energy-related data, both historical and predictive, which serve as inputs and outputs for the tools integrated into the system. By aggregating this data, the database becomes a central hub for energy analysis, supporting various operations, including energy forecasting, optimization, and reporting.

Furthermore, it efficiently manages predictions generated by analytical tools, storing them alongside historical data to facilitate comparison and trend analysis. The database efficiently manages the integration of time and location variables with various energy metrics, allowing for a comprehensive analysis of energy data across spatial and temporal dimensions. Energy data, such as consumption and generation, is linked to specific geographical locations and time intervals, providing a detailed view of energy trends by region and period. This connection enables the tools to offer more targeted insights.

Design of the database schema also supports the flexibility in terms of time granularity, allowing it to store data at varying time intervals, from hourly snapshots to annual summaries. While the current setup has predefined hourly time granularity settings, the schema is designed with future adaptability in mind, ensuring that any changes in time resolution can be easily accommodated. This flexibility ensures the database remains relevant as energy monitoring practices evolve and more granular data becomes necessary.

In order to enable seamless data ingestion, custom scripts have been developed which are capable of handling different file formats, ensuring compatibility with various sources of information. The process of importing data into the database is a collaborative effort between BrainIT, the tool developers, and other contributing partners who supply historical and relevant data. BrainIT also evaluates the final results of the import process, applying industry-standard practices to ensure secure and consistent data ingestion. As the data ingestion process is highly dependent on the actual input data, data source and formats of the input data, it will be further refined as more data becomes available for analysis.

On the other hand, custom export scripts are used to transform and output data in formats compatible with each tool's specific input requirements. These scripts streamline the data extraction process, ensuring that tools can quickly access the information they need without requiring manual data handling or manipulation.

By offering this level of interoperability, the database enhances the efficiency of tool operations and reduces the likelihood of data inconsistencies.

Data stored in the database

The database stores a diverse set of energy-related data, categorized to support in-depth analysis. It incorporates universal timestamps and standardized location values to ensure consistency across all datasets. Energy types, currently including electrical and heat energy, are categorized alongside energy

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sources data, distinguishing between renewable and non-renewable energy. The database also tracks energy consumption profiles across various sectors, such as residential, industrial, and public buildings, ensuring a broad representation of energy use. Electricity generation and consumption data are crucial components, with detailed information on the mix of technologies (such as the percentage of each of the energy sources in the current network), generation costs, distribution costs, and the demand and capacity of energy systems. Additionally, the database records the amount of energy consumed, stored, imported, and exported, offering a complete view of the energy flow within a given region.

Finally, the database also stores essential geographical, climate, and socio-economic data, which are necessary for the operation of various analytical tools within the project. This type of data provides important contextual information that enhances the accuracy of the tool's predictions and analyses. For instance, geographical data provides information about the available land across regions, while climate data is used to understand environmental factors that influence energy demand and generation. Socio-economic information enables tools to assess how economic and demographic conditions affect energy consumption patterns.

By incorporating these diverse datasets, the database ensures that the tools have a comprehensive foundation for generating meaningful insights and making informed decisions.

Technical aspects of the database

Currently, the database is operating on a development virtual machine instance, serving as the central hub for data storage, management, and security. Access to the data is secured through SSH key-based authentication, ensuring that only authorized users, such as developers and key stakeholders, can establish secure connections. At this time, stakeholders do not have the ability to directly manipulate the data within the system. Should the need for direct data manipulation arise, an appropriate mechanism will be implemented, likely in the form of a backend solution or custom scripts, depending on the specific requirements. The database infrastructure has been designed with scalability and robustness in mind, featuring a flexible schema and scalable cloud infrastructure. These features allow for quick and efficient adaptation to the evolving needs of stakeholders. The underlying architecture also supports the seamless addition of new data and modifications to the schema, ensuring the system remains flexible and adaptable as the project progresses.

Current state and schema

The database is in a preliminary state, but its structure is already capable of storing all necessary data to support current needs. The schema has been defined to ensure that it can accommodate the wide variety of data types required for energy analysis, from consumption profiles to electrical grid topologies. This foundational structure positions the database as a central component of the project’s data management strategy, ensuring that all tools have access to the data they need to operate effectively and that future developments can be easily integrated into the system. Current state of the database will be further developed and defined in the next version of Deliverable D2.2 (Database), which is being led by BrainIT and is scheduled for completion by M24 (November 2025).

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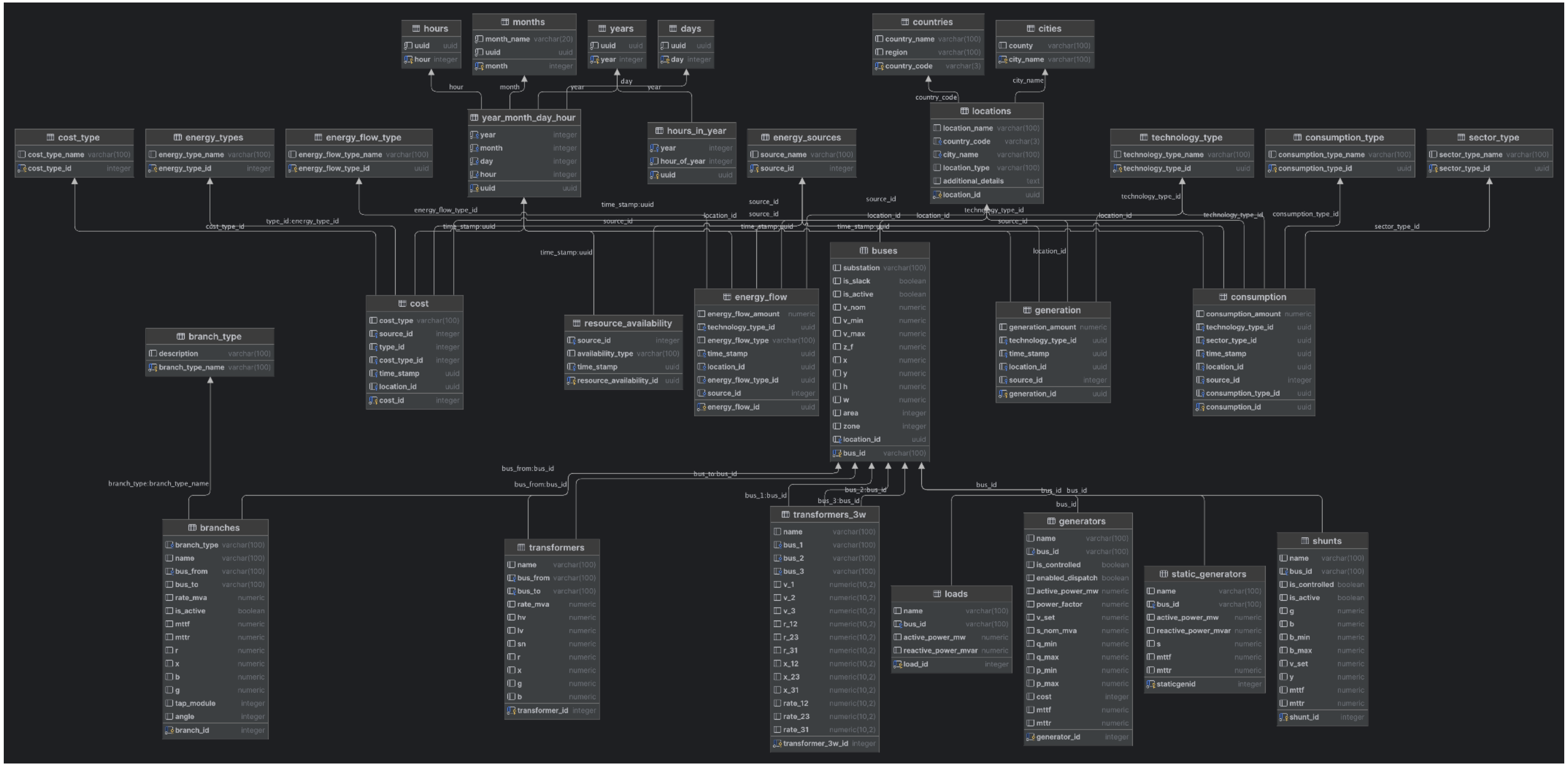

Figure 12 - Preliminary central database schema

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6. Conclusion

This deliverable presents the outcomes from the Tasks T2.1 - Analysis of existing databases and models, T2.2 - Defining a Common System Architecture (CSA) and T2.3 - EMERGE database development.

The first part of the report contains an overview of the context of energy modelling in the African Union (AU) which can contribute to the objectives of developing a more sustainable and reliable energy infrastructure and also to decreasing the energy access inequality between countries and especially between rural and urban areas. EMERGE project will be adapted to the different energy context and challenges of the pilots; namely Mozambique in East Africa, Morocco in the North-Western Africa and Mali and Nigeria to represent the Niger river region. Main identified challenges are listed below:

- In *Mozambique*, inadequate power infrastructure remains a significant hurdle, with high connection fees and lack of investment, limiting access to the grid. Energy access is a critical issue, particularly in rural areas where only 5% of the population has electricity, mainly due to country's sparse population density, low urbanization, and widespread energy poverty. Additionally, the absence of a transparent regulatory framework undermines effective policy implementation and investor confidence, hindering the efforts to improve the energy sector.
- In *Morocco*, the focus is on reducing the country's reliance on fossil fuel imports while simultaneously promoting local economic growth and job creation. To achieve these goals, there is a need to establish comprehensive frameworks for policy development, education, and research and development (R&D). Community engagement is also crucial in supporting these objectives and ensuring sustainable progress.
- In the *Niger River region*, the challenges revolve around defining actions for climate change mitigation and adaptation. The region faces issues related to land occupation for farming, particularly in lowlands and along riverbanks, and the massive clearance of forests for agricultural purposes. Artisanal gold mining in river courses poses additional environmental risks, while water losses in the Inland Delta, exacerbated by other construction activities, threaten the region's water resources. Addressing these challenges is vital for the sustainable management of the Niger River and its surrounding ecosystems.

The report then continues with an analysis of existing energy-related models, open databases and projects addressing AU-EU collaboration. From this research, some key historical trends in energy consumption, production, and other relevant data for energy modelling in the African context. Some of the main challenges for energy modelling in AU identified during the analysis are listed below:

- *Lack of accurate data:* The availability of open databases to obtain the necessary data is one if the greatest challenges, especially in terms of geographical coverage, since the spatial representation of African countries is normally conducted as aggregates or regions, leading to supra-regional databases instead of country-level datasets.
- *Inequality in the energy access:* The access to electricity is one of the major goals for sustainable development on the African continent. This challenge is even more pronounced in rural areas, where the bulk of the population is established.
- *Economic metrics:* Energy modellers usually use Gross Domestic Product (GDP) as driving factor to simulate energy demand trends. This parameter may be appropriate for industrialised countries, but not for African nations in which the usual methods for calculating the GDP frequently underestimate true economic activity, especially where informal employment is common, resulting in wrong demand assumptions. Because of that, a more context-specific analysis is needed for each country.

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- *Capacity-building:* Capacity building has been defined as critical towards promoting sustainable development, being essential the creation of a pool of local experts in energy modelling. This approach aims to facilitate the establishment of partnerships between local academic organisations and African institutions to learn and apply best practices in future energy planning.

Then the methodology for the definition of the *Common System Architecture* (CSA) was defined in three different steps from *model classification* (1) to *feature mapping* (2), and finally the *soft-linking* of the tools (3). The objective of the CSA is to create a framework that will help on the database creation and connection of the different project tools to develop the *EMERGE Toolbox*.

This process involved the evaluation of 14 tools, including those of the project that will constitute the *EMERGE Toolbox*. During this analysis, the tools and models were defined and classified to identify the most relevant and common features among them. Soft-linking diagrams were then developed to highlight duplicities and potential links between them, by connecting the outputs of one tool as inputs of the others.

The last section of this deliverable includes an overview of the EMERGE project database, its development status and preliminary scheme. This structure is already adapted and capable of storing all necessary data to support the *EMERGE Toolbox* current needs.

In summary, this report identifies and validates the essential components that will drive the development of the *EMERGE Toolbox*, with particular emphasis on the local context of the pilot sites and the technical requirements of the individual project tools.

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