International Renewable Energy Agency

Advancements in continental power system planning for Africa

Methodological framework of the African Continental Power Systems Masterplan's SPLAT-CMP model 2023

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ABBREVIATIONS

AC	alternating current
ACEC	African Clean Energy Corridor
AfREP	African Renewable Electricity Profiles
AfSEM	African Single Electricity Market
AU	African Union
AUDA-NEPAD	African Union Development Agency – New Partnership for Development
CAPEX	capital expenditure
CAPP	Central African Power Pool
CCGT	closed-cycle gas turbine
CF	capacity factor
CMP	Continental Masterplan
COMELEC	Comité Maghrébin d'Électricité
CSP	concentrated solar power
DNI	direct normal irradiation
EAPP	Eastern Africa Power Pool
EEZ	Exclusive Economic Zone
EU	European Union
EU GTAF	European Union Global Technical Assistance Facility
GHI	global horizontal irradiation
HFO	heavy fuel oil
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IAEA	International Atomic Energy Agency
IIASA	International Institute for Applied Systems Analysis
IRENA	International Renewable Energy Agency
kW	kilowatt
LCOE	levelised cost of electricity
LL	line loadability
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MSR	Model Supply Region

MW	megawatt
MWh	megawatt hour
NREL	National Renewable Energy Laboratory (US)
OCGT	open-cycle gas turbine
OSeMOSYS	Open Source Energy Modelling System
PV	photovoltaics
RCP	Representative Concentration Pathway
RoR	run-of-river
SAPP	Southern Africa Power Pool
SIL	surge impedance loading
SM	solar multiple
SNSP	system non-synchronous penetration
SPLAT	System Planning Test
SSP	Shared Socioeconomic Pathway
TW	terawatt
UN	United Nations
USD	United States dollar
VRE	variable renewable energy
WAPP	West African Power Pool
WETO	World Energy Transitions Outlook
WACC	weighted average cost of capital

ABOUT THIS REPORT

This report provides detailed insights into the design and setup of the System Planning Test-Continental Masterplan (SPLAT-CMP) model, the underlying optimisation model of the Africa Continental Master Plan (CMP) for electricity generation and transmission. CMP is an initiative tasked to the African Union Development Agency – New Partnership for Development (AUDA-NEPAD) as per the recommendations adopted by the African heads of state at the 34th Ordinary session of the Assembly of Heads of State and Government of the African Union in 2021. Subsequently, in the 37th Ordinary session of the Assembly, the CMP was formally adopted as an African Union Agenda 2063 flagship project.

The CMP initiative was undertaken to support the AU African Single Electricity Market (AfSEM) initiative launched in June 2021. The African power pools are actively involved in the CMP process with a view to aligning modelling and planning processes with regional policies and initiatives. Alongside the designated staff of AUDA-NEPAD, the official CMP modelling team includes representatives from WAPP (West African Power Pool), SAPP (Southern African Power Pool), EAPP (Eastern Africa Power Pool), CAPP (Central African Power Pool), COMELEC (Comité Maghrébin d'Électricité) member countries, and EU-Global Technical Assistance Facility (EU-GTAF).

IRENA and the IAEA support the CMP initiative as officially endorsed modelling partners.

The first CMP exercise entailed three planning analyses: (i) demand projections, (ii) generation and cross-border transmission expansion optimisation, and (iii) network studies (further explained in Box 1). Based on agreed tool selection criteria finalised during the consultations that formed part of the CMP process (Box 2), the stakeholders selected IRENA and IAEA's SPLAT-MESSAGE framework for the generation and cross-border transmission expansion analysis.

To this end, IRENA combined its pre-existing power system capacity expansion models for 50 African countries,[1] the so-called System Planning Test (SPLAT) models, into one SPLAT-Africa model to serve as a starting point for CMP modelling. Over the course of two years, the CMP modelling team received hands-on training from the modelling partners on the development and use of the SPLAT-Africa model. The CMP process entailed many virtual and in-person stakeholder engagement events and day-to-day teamwork among the staff of AUDA-NEPAD, the power pools and North African country representatives. This enabled the CMP modelling team to update the SPLAT-Africa model into the so-called **SPLAT-CMP version 2023**. During the process, the model was equipped with up-to-date information collected on 48 African countries.[2]

By providing a detailed description of the methodology behind the SPLAT-CMP model, this report aims to enhance the transparency and the reproducibility of the modelling results. It will also enable the CMP stakeholders to better understand the model results and inspire its future use in the next CMP exercises. The

[1] *All Africa except Madagascar, Mauritius, the Comoros and the Seychelles.*
[2] *All SPLAT countries except Cabo Verde, and São Tomé and Príncipe.*

report also complements the efforts behind the recently developed web-based user guide for the SPLAT interface, available at https://splat-tutorial.readthedocs.io/en/latest/. The SPLAT interface is an Excel based interface required to implement the SPLAT modelling framework, as well as to control and visualise the model contents and results respectively.

The final modelling results – as well as the model inputs and their basis, as finalised by the CMP modelling team and agreed with the broad stakeholders – are documented in a separate series of reports prepared with the financial assistance of the European Commission (AUDA-NEPAD, 2023a, 2023b, 2023c). The report series is hosted online at the centralised database "Mwanga" of AUDA-NEPAD, developed specifically to facilitate data exchange among CMP stakeholders in the future (https://cmpmwanga.nepad.org/).

This report is structured as follows: Section 1 provides an overall introduction to the SPLAT model framework and the rationale for selecting it for CMP purposes; Section 2 describes in detail all new model elements that were introduced in the SPLAT-CMP model; Section 3 goes on to describe the practicalities of and strategies for setting time slices for running the SPLAT-CMP model, allowing for practical runtimes while retaining adequate spatio-temporal resolution; Section 4 describes model version control; Section 5 summarises possible strategies for further model improvement; and Section 6 concludes with a future outlook.

Box 1 Analyses and tools involved in the first CMP exercise

In the technical planning for a vision of a continentally integrated African power grid, various elements needed to be considered separately with their own suitable model approaches. Consequently, in the first CMP exercise, AUDA-NEPAD was charged with developing three distinct pillars of planning:

(1) electricity demand projections for every continental African country up to 2040

(2) long-term capacity expansion planning scenarios for power generation and cross-border transmission infrastructure up to 2040 to meet the projected demand

(3) network studies to confirm the technical feasibility of the cross-border interconnectors selected in the capacity expansion optimisation scenarios.

The demand assessment analysis performed using EViews defined the future electricity demand projections in various scenarios. These included a baseline trajectory as reference case (AUDA-NEPAD, 2023d) and three alternative scenarios (AUDA-NEPAD, 2023e) reflecting low, medium and high aspirational targets on various development aspects, such as electricity access rates and per-capita income growth.

The power system capacity expansion analysis performed using the SPLAT-MESSAGE framework identified cost-optimal prospects for new generation capacity, cross-border interconnection and storage assets up to 2040 under various scenarios (AUDA-NEPAD, 2023a, 2023b). As a capacity expansion model, the SPLAT-CMP model mainly assessed the cost implications associated with the buildout of the scenario capacities without deep diving into the engineering aspects of grid operation. Nevertheless, certain important operational and engineering aspects were accounted for in a simplified way, *i.e.* the planning reserve constraint (Section 2.2.1), the upper bound on instant penetration of variable renewables (Section 2.2.2), and others.

Box 1 Analyses and tools involved in the first CMP exercise (continued)

The network analysis performed using the PSS®E tool aimed to refine and validate the SPLAT-CMP results. It carried out an engineering analysis covering steady-state system studies to assess potential grid reliability gaps, such as the various critical contingencies involving loss of major generators or transmission lines across different parts of the continental grid system (AUDA-NEPAD, 2023f). Advanced studies, such as transient and frequency stability studies, were outside the scope of the analysis.

In addition to the above three analyses, the CMP exercise also developed a methodology for cost–benefit-based ranking of the candidate generation and interconnection projects of key relevance in the medium term, being 2023-2032 (AUDA-NEPAD, 2023g). This analysis was used to evaluate the internal rate of return (IRR), net present value (NPV), and other financial metrics/indicators of the projects. This analysis differed from the SPLAT-CMP analysis in the sense that it evaluated the priority of the projects from an investor's perspective instead of the system value perspective. The cost–benefit study aimed to inform the next steps in the CMP process, which would focus on a multi-criteria ranking of the projects for their further integration into the various infrastructure facilitation mechanisms in progress in Africa.

Box 2 Tool selection considerations of the CMP stakeholders (AUDA-NEPAD, 2023c)

While selecting the various models to carry out the CMP exercise, the CMP stakeholders paid particular attention to maintaining uniformity with the tools and models already utilised and/or selected for updating the individual power pool masterplans. The detailed criteria included the following considerations:

i. **Functionality:** Is the model fit for purpose for the job to be undertaken and can the model handle all the major issues that need to be modelled?

ii. **Cost of licences:** Is the cost of potential licences prohibitive, given the need for training for a given number of personnel and the need for the maintenance of databases?

iii. **Transparency of the model:** Is the modelling methodology sufficiently documented? Can it be used to understand the expected outcomes of the model?

iv. **Reliability of the model:** Can the model be used to confirm/validate known outcomes from past modelling approaches? Can it run properly without non-convergence issues, and would the results remain insensitive to different model versions?

v. **User-friendliness of the model:**

- Can data easily be entered in the model, including bulk changes, and can the results be made available in an accessible format that can be directly used in reports or presentations?
- Does the model have a robust standard set of plots and tables to allow the results to be reviewed in an accessible manner?
- Does the model produce reports that can be easily customised for various applications?
- Does the model have a (graphical) interface?

1. THE SPLAT-CMP MODEL FOR THE AFRICAN CONTINENTAL POWER SYSTEMS MASTERPLAN

The SPLAT models are country-specific generation capacity expansion models covering the entire African continent and are routinely used by IRENA for national and regional capacity-building programmes in Africa (IRENA, n.d.a), and the Planning and Prospects for Renewable Power in Africa analyses (IRENA, n.d.b). The SPLAT models were created utilising a model generator called the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE). MESSAGE is a versatile, adaptable, bottom-up, multi-year energy system model that utilises linear and mixed-integer optimisation techniques. It was first established by the International Institute of Applied System Analysis (IIASA), but has been subsequently improved by the International Atomic Energy Agency (IAEA).

For modelling power systems, the MESSAGE software needs a projection of demand, a database of current capital assets for power generation and transmission, technical and economic specifications of power supply technologies, and a list (along with technical and economic specifications) of future investment options for power generation and transmission for the model to invest in. MESSAGE aims to minimise the net present value (subject to a user-defined overall discount rate) of total system costs incurred to meet a user-defined level of demand over a given planning horizon and under a specific set of assumptions. A MESSAGE user guide courtesy of the IAEA is publicly available (IAEA, 2016). MESSAGE is a free-of-cost tool for IAEA member states and supports working with free programming solvers.

Starting from the power infrastructure in a chosen base year in a given region, a MESSAGE-based model computes a progression of possible technology combinations per period (user-defined; typically yearly) that can achieve the lowest-cost objective across the planning phase to meet user-defined demand and constraints. The constraints can represent technical constraints linked to power system operation, but may also policy assumptions that reflect scenario storylines. While the model can technically run at full hourly resolution, it is typically run using time slice-based approaches to avoid unrealistic computational requirements (see Section 3 for more details). These time slices usually represent "common" daily and seasonal variabilities in power generation and demand.

The model produces the lowest total discounted cost[3] of the system, which includes investment, operation and maintenance, fuel, and any other costs defined by the user (*e.g.* penalties on greenhouse gas emissions; costs of unmet demand). Additionally, it ensures that all system requirements are met, such as sufficient resources and capacity to achieve desired production levels, meeting a user-defined reserve margin, or staying within user-defined technology deployment limits, as well as any policy objectives that the user may define (*e.g.* renewable energy targets, CO_2 emission limits, speed of technology rollout).

[3] *Discounting is a process of converting a cost value projected to incur in the future into an equivalent current value. In the CMP model, the base year of 2019 reflects the "current", and the various costs anticipated to incur in different years across the study period are brought to 2019 equivalents assuming a fixed discount rate described in Section 2.3.4*

The SPLAT-CMP model was designed in a versatile and flexible way to control model inputs and outputs, and allow configuration of runs with any combination of African countries. The ultimate goal was to run scenarios at the continental level and examine suggested investment strategies in new generation and cross-border transmission projects under various scenarios. The model was established by merging previous versions of the SPLAT model for individual African power pools, documented in IRENA's report series on planning and prospects for renewable power in Africa: SPLAT-W for the West African Power Pool (IRENA, 2018), SPLAT-ACEC for the African Clean Energy Corridor, consisting of the Eastern and Southern African power pools (IRENA, 2021a), SPLAT-C for the Central African Power Pool (IRENA, 2021b), and SPLAT-N for North Africa including COMELEC countries (IRENA, 2023b).

The SPLAT-CMP model includes a number of updates as compared to previous SPLAT models, and some state-of-the-art modelling features that may benefit the energy modelling community.

2. ELEMENTS OF SPLAT-CMP MODEL DESIGN

2.1 POWER SYSTEM DESCRIPTION

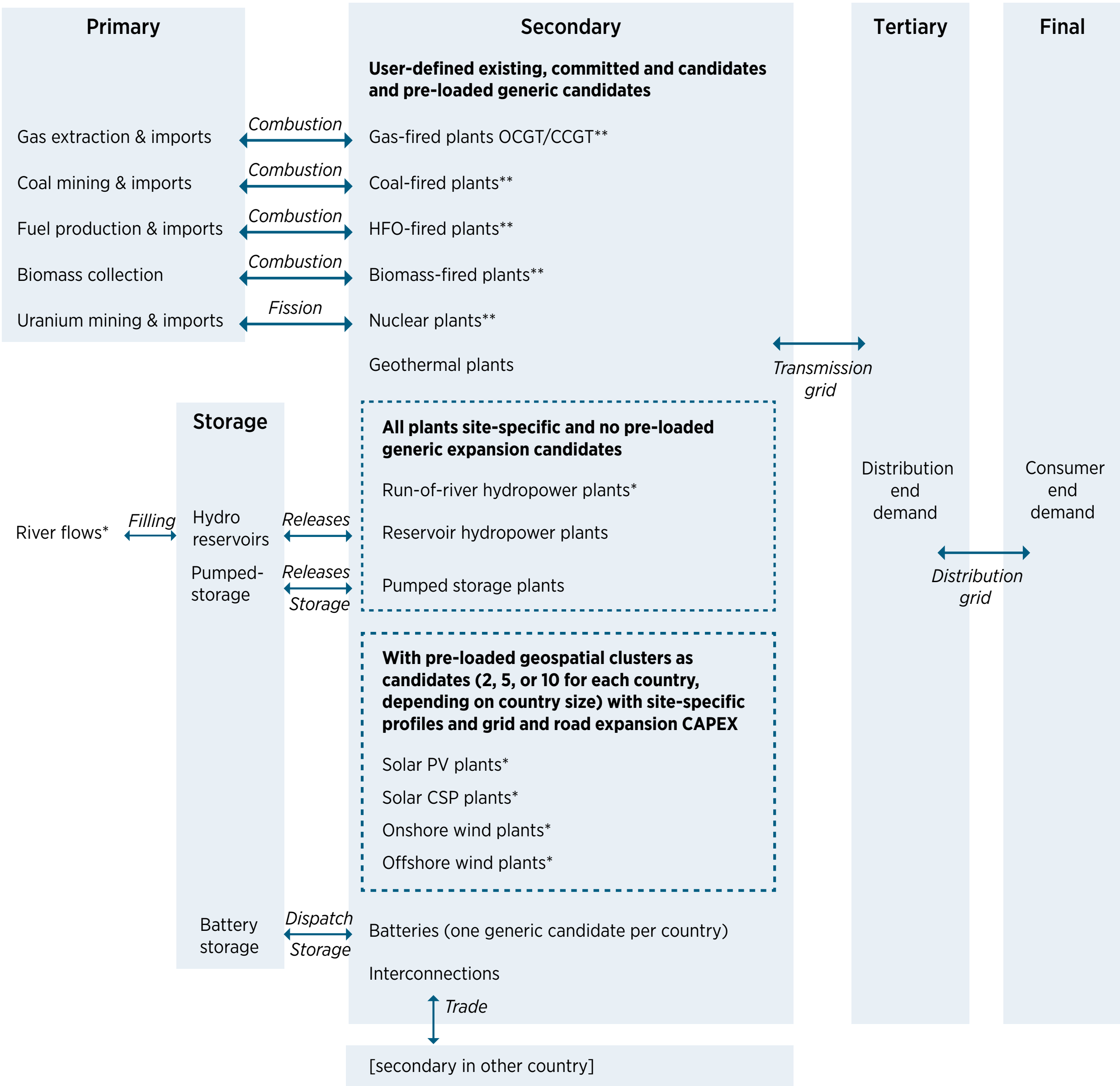
In the spirit of previous SPLAT models, the SPLAT-CMP model in its simplest form can be represented as follows. Each country is represented as a single node containing different energy "levels", which represent energy at the resource level (primary), energy converted into electricity by power plants (secondary), electricity at the transmission level (tertiary), and electricity at the distribution level (final). These energy levels, along with various other model elements (see below), are schematically shown in Figure 1.

The **primary** level represents the availability of resources (measured in terms of primary energy supply) at each country node level. The availability of these resources is determined both by domestic resources as well as a country's capacity for imports, *i.e.* by exogenous constraints. Fuel prices are exogenously set at this level. In the SPLAT models, as a default, fuel prices are differentiated by fuel type and by local production versus imports, but not differentiated on a country basis (*i.e.* country-level subsidies or other price distortions are not reflected in the model).

The **secondary** level is the most important in the model, as it contains all the power generation assets within a country that convert a resource (primary level) into electricity ready to feed into the transmission grid (tertiary level). It not only contains *existing* power generation assets, but also *committed* assets (specific plants that are not online yet, but which are considered as coming online in the future with complete certainty in a known year; the definition of *committed* according to the CMP planning process is a plant that has reached financial close) as well as all *candidate* technologies, among which the model can choose a selection to cover the future supply–demand gap. In addition to user-defined *candidate* capacity, SPLAT-CMP model entails pre-loaded generic candidate supply options for most generation technologies to allow the user to design the expansion optimisation according to specific scenario definitions.

For all technologies that are due to come online in the future, a construction time (number of years) is assumed, and the optimisation thus accounts for the construction starting before the year of deployment. The interest expense during construction is computed by the model assuming that the overnight capital expense is distributed equally during the construction period (including the year in which the technology comes online). The interest expense together with the overnight capital expense of the technology is eventually annualised and the resulting annualised costs incurring each year during the project life period are brought to a common base year by discounting (see Section 2.3.4 for more details on discount rate parameter) for the purpose of making optimization decisions. The construction times differ by technology, representing the complexity of the engineering involved in different types of power plants. We note that only engineering construction times were considered, whereas in reality, planning and regulatory approvals tend to take (substantially) more time, especially for nuclear power plants and large hydropower plants.

Figure 1 Schematic overview of the RES (Reference Energy System) of each country node in the SPLAT-CMP model



* These technologies are provided with a specific temporal availability profile (see Section 2.3), **Generic capacity expansion is allowed subject to stakeholder's preference.

Notes: HFO = heavy fuel oil; OCGT = open-cycle gas turbine; CCGT = closed-cycle gas turbine; PV = photovoltaic; CSP = concentrated solar power.

The candidate technologies are modelled in a few distinct ways, depending on the specific technology:

(i) Generic candidate power plants running on gas, coal, HFO, diesel and biomass, as well as candidate nuclear power plants, are modelled as "generic" technologies. "Generic" means that no technological, geographical or economic distinction is made in the cost characteristics between different individual "candidate" plants; the generic candidate technology is a lumped category that covers all future possible power plants of that technology which do not fall under the user-defined site-specific "committed" or "candidate".

(ii) Candidate hydropower power plants are modelled as site-specific. Since it is not meaningful to speak of "generic" hydropower potential, given that every hydropower plant has very specific characteristics and output profiles (see Section 2.3 below), the potential for building new hydropower plants across Africa has been appraised at the level of individual plants, and each of these plants is separately included in the model, both for run-of-river and for reservoir hydropower plants. The latter requires inclusion of river flow dynamics and reservoir filling dynamics in the MESSAGE modelling framework. Like hydropower, candidate geothermal plants are also modelled at the individual project level according to an appraisal performed under one of the CMP specific support studies of possible future projects in Africa, mainly in the countries with commercially exploitable geothermal potential straddling the East African Rift: Djibouti, Ethiopia, Kenya, Tanzania and Uganda (EU GTAF, 2023a).

(iii) A wider candidate capacity pool of renewable technologies is modelled as regional "clusters" of high-potential sites whose potential is spatially divergent but less site-constrained than hydropower and geothermal – namely solar PV, CSP, onshore wind and offshore wind. Given that these technologies' potential can cover large swathes of a country's surface area, as opposed to that of, say, hydropower (which is restricted to locations where rivers undergo altitude drops), the most attractive areas of potential were identified for each country and grouped into a number of clusters with comparable production profiles. Each of these clusters serves as an individual pre-loaded generic "candidate" supply option in the model with its own techno-economic parameters. The number of region-specific clusters thus obtained varies by technology and country in the range of two to ten (see Section 2.3 below). In addition, a limited capacity of user-defined project-specific candidate solar PV, CSP and onshore wind is represented in the model, characterised according to stakeholder inputs during the CMP process.

Certain technologies require a temporal profile to model their availability on diurnal and/or seasonal timescales (indicated with an asterisk in Figure 1). This includes all solar and wind technologies and run-of-river hydropower, as well as the river flow technologies feeding hydropower reservoirs (see Section 2.3 below). The profiles for site-specific technologies are therefore uniquely defined, reflecting each site's meteorological and hydrological conditions.

The secondary level also contains *storage* technologies. These comprise regular hydropower reservoirs (see above), pumped-storage (off-river) hydropower, and battery storage. Similar to the "river technology" used to model reservoir hydropower, battery storage technology is linked to a certain energy per power ratio to control the length of storage duration (see Section 2.5 below). Candidate battery storage schemes are modelled generically, similar to thermal power plants, with one 4-hour storage technology per country.

Last, the secondary level of a given country node is connected to the secondary level of its neighbouring countries through technologies representing *cross-border interconnections*. These are divided into existing, committed and candidate technologies based on previous SPLAT databases and stakeholder inputs; and generically characterised candidate technologies (*generic interconnections*), connecting all neighbouring country pairs, to allow the model to select from an uncapped pool of interconnection capacity in certain CMP scenarios. For instance, Ethiopia shares borders with six countries (Eritrea, Djibouti, Somalia, Sudan, South Sudan and Kenya), and hence the model contains six generic interconnector technologies from Ethiopia to elsewhere. Generic interconnectors are differentiated in CAPEX (USD/MW) terms based on length, terrain and the assumed design voltage (see Section 2.4 below).

Within each node (country), we use the copper-plate assumption, presuming perfect internal transmission.[4] This assumption is not reflective of the situation on the ground in many African countries; hence it is among the elements for potential future improvement in the SPLAT-CMP model (see Section 5). The SPLAT-CMP model can therefore only provide information about strategies to increase cross-border transmission infrastructure, not domestic transmission and distribution infrastructure.

The **tertiary** level represents the bulk domestic demand on the distribution grid to be served via the domestic transmission grid by wheeling electricity from utility-scale generators and cross-border interconnections. A loss factor between secondary and tertiary level accounts for transmission losses. The **final** level operates similarly, representing the bulk consumer end demand to be served by the domestic distribution grid, accompanied with a loss factor reflecting distribution losses. Although previous versions of the SPLAT model distinguished between various demand categories such as urban, rural, commercial, and industrial, under the CMP project the country-level demand projections were estimated at the "sent-out" level instead of the consumer end user level using a top-down econometric analysis. As a result, the sent-out demand, which is the demand seen by the generators and the cross-border interconnections before any wheeling through the grid, was inserted at the **final** level in the model alongside setting the transmission and distribution loss factors to zero.

2.2 MODELLING METHODOLOGY UPDATES: CONSTRAINTS AT THE SYSTEM AND COUNTRY LEVEL

The SPLAT-CMP model also contains various systematic constraints, both at the node (country) level and at the system (continental) level, to simulate various real-life constraints on power system operation. The most important constraints are the **reserve margin**, the **speed of technology deployment**, and the **instantaneous variable renewable energy (VRE) penetration**.

2.2.1 Reserve margin

During operation, power systems need various kinds of operational reserves to meet a range of contingencies, such as the sudden loss of a generator or unavailability of generators due to planned and unplanned outages. Although the sizing requirements of different types of operational reserves are best assessed through the hourly production cost models (IRENA, 2017), most country grid codes provide a ballpark estimate of the margin of reserve generation that needs to be maintained above the actual generation requirements. The SPLAT models, like many traditional capacity expansion models, employ such a reserve margin constraint to account for the need for operational reserves in the projected generation mix on annual basis. Any scenario produced by the SPLAT-CMP model must meet this reserve margin constraint, which is applied both at the *node level* as well as at the *continental level*.

Different technologies are considered to have different capacity credits and thus contribute to this reserve margin in different ways – *e.g.* thermal and nuclear power plants can provide more "firm" capacity (guaranteed to be available to meet demand) than solar or wind power plants. Cross-border transmission lines can also contribute to the reserve margin (so countries can invest in cross-border transmission to improve system reliability). This applies only at the node (country) level, since a country could conceivably meet part of its reserve margin by relying on its neighbours' capacity, whereas at the continent level internal transmission cannot be assumed to provide this margin.

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[4] *The "copper-plate" assumption refers to the simplification that power can flow unconstrained from any generation site to any demand site.*

The continental reserve margin constraint is a new feature in the SPLAT-MESSAGE framework. It was introduced to limit the tendency for unrealistic expansion of generic interconnection capacity. In past SPLAT applications (IRENA, 2018, 2021a, 2021b, 2023b), the issue of unrealistic expansion of interconnector capacity was not encountered as the interconnections inserted in the model were limited to existing or planned projects.

The SPLAT-CMP model uses a default minimum reserve margin constraint of 10% above the peak load at the continental level and the country-level.[5] The value of 10% was modified country-wise in the CMP model according to stakeholder preferences. Table 1 gives an overview of the default reserve margin contributions of the different technologies used in the SPLAT-CMP model. In modelling terms, the reserve margin was implemented in SPLAT-CMP through a constraint in which each built unit of generation and interconnection capacity contributes a certain share of its capacity to the overall reserve margin, which must reach at least 10% of the peak demand in each year.

Table 1 Overview of reserve margin contributions of the various technology types used in the SPLAT-CMP model for the CMP process

Technology	Reserve margin contribution	Notes
Conventional generation		
Gas	100%	This assumption reflects the practice adopted in the past regional master plans of Africa. This is a somewhat optimistic assumption, as in reality all power plants will have certain outage rates that will in practice also de-rate the reserve margin contribution.
Coal	100%	
HFO/diesel	100%	
Nuclear	100%	
Biomass	100%	Seasonality in the availability of biomass, which could constrain the availability of biomass power plants in off-cropping seasons, is not considered in the model.
Hydropower (run-of-river)	100%	This is an optimistic assumption. In reality, the reserve margin contribution of run-of-river hydropower plants depends strongly on the river seasonality. While this seasonality itself is part of the model, its effect on the seasonality of the reserve margin contribution was not modelled.
Hydropower (reservoir)	100%	In reality, the reserve margin contribution of reservoir plants would depend on the precise interplay of river flow seasonality, reservoir size and reservoir operation. This was not considered in the model.
VRE generation		
Solar PV	0%	Given that solar PV output is guaranteed to be zero at night-time, it is allocated a zero capacity credit. In reality, solar PV could contribute to the reserve margin if peak demand were guaranteed to take place during hours of high solar insolation (GET.transform, 2023). This effect was not modelled.
Onshore wind	0%	This is a conservative choice, as wind power is often deemed to have a somewhat higher-than-zero reserve margin contribution and, depending on the geography, may generate in peak load hours (EU GTAF, 2023b).
Offshore wind	0%	

[5] *Peak load at the continental level was calculated as the sum of all the peaks of individual countries' load curves.*

Technology	Reserve margin contribution	Notes
Technologies with storage		
Pumped hydropower	75%	In principle, this is a system-dependent factor. The modelling choice taken here is meant to reflect the important point that it should be non-zero but less than 100%.
CSP with 6 hours storage	75%	
Batteries with 4 hours storage	75%	
Trade		
Interconnections to neighbours	50%	Reserve margin contribution of interconnectors is only applied at the country level constraint (node level), not at the continental level constraint (since the interconnectors represent connections to other systems at the country level but represent internal transmission at the continental level). In the case of countries with high installed capacity being surrounded by countries with much smaller systems, we recommend potentially deviating from this rule and giving a zero reserve margin contribution to generic interconnectors also at the country level. In the SPLAT-CMP model, this was done for South Africa.

Note: The numbers represent the percentage of the technology's installed capacity that counts towards the installed reserves.

2.2.2 Instantaneous VRE penetration

Given concerns about frequency and voltage stability on the power grids, some system operators already practice instantaneous VRE penetration limits; for example, the grid operator of the Republic of Ireland has the so-called System Non-Synchronous Penetration (SNSP) limit currently set at 75%. Given that the grids of many African countries are characterised as low-inertia grids, the SPLAT-CMP model contains the option of limiting the instantaneous penetration of VRE in each country's power system.

Based on stakeholder consultations in the CMP process, the instantaneous VRE penetration limit of 70% was adopted without any variation across countries or the modelling years. Given the already rapidly evolving global experience of and solutions to integrating high shares of VRE production in power systems, this assumption can be regarded as a conservative estimate, especially for the final years of the CMP study period. For example, in the case of Ireland, the development of interconnectors to the United Kingdom and continental Europe, as well as the deployment of storage capacity, have been proposed as levers for increasing the SNSP limit (Kenny, 2023). Similar considerations may thus apply to the African continent in the long term.

2.2.3 Technology deployment speed for VRE and biomass technologies

The model contains maximum annual buildout rates for the solar and wind generation technologies currently undergoing rapid cost reductions (solar PV, CSP, onshore wind and offshore wind). The rationale behind this is that the falling cost curves can make it attractive for the model to invest "in bulk" in these technologies in a given year, leading to spurious model results in which the capacity of one country's power system is doubled or tripled within a single year. This effect was observed for roughly one-third of countries during model tests without annual build limits. Constraining the annual deployment speed (in MW/year added) of solar and wind technologies to a certain maximum, therefore, leads to smoother and more realistic year-on-year capacity buildout curves. This model constraint reflects a real-world constraint, because countries would in practice not be able to finance or build extremely large amounts of renewable capacity within limited time periods, given constraints on the availability of skilled workers and the manufacturing/import of necessary materials and other logistics such as the availability of cranes.

Maximum deployment speeds for the solar and wind technologies are modelled at individual country level. These maximum speeds are modelled to increase from year to year in line with the growing size of a country's power system. The default maximum capacity deployment speed of solar and wind technologies used in SPLAT-CMP was 25% of the peak demand of the previous year. This default was corrected upwards in all cases where it would have otherwise contradicted the capacity coming online from large, committed projects.

Aside from solar and wind technologies, annual build limits were also imposed on the buildout of biomass-based plants. For this purpose, a simple approach was adopted that did not include details on seasonality of biomass availabilities or land use competition between energy and non-energy use. The approach was as follows: first, historical sugar production was assessed at a country level (ISO, 2020) and production per capita was calculated. Assuming this ratio to remain constant, sugar production was then extrapolated across the model period using UN population projections (UN, 2022). Sugar tonnage was then converted to sugar cane tonnage and then to electricity production potential based on reported empirical ratios (IRENA, 2019). Lastly, this yearly potential in MWh/year was converted to buildout potential in MW/year, assuming a 65% capacity factor (CF) (IRENA, 2021a). Non-bagasse-based electricity generation from biomass was not considered in the model.

2.2.4 Other constraints

A few other generic specifications at the power plant-level were implemented to account for operational dynamics not captured explicitly, given the level of detail used in the SPLAT-CMP model.

The first specification was to include a minimum utilisation rate for all thermal plants. This was to capture operations (and corresponding fuel combustion, costs and emissions) occurring during contingency conditions that mainly arise from sudden unexpected/unplanned outages of other units in the system or from large unexpected fluctuations in demand or VRE resource availability, as well as the fact that the model works with deterministic scenarios in which random fluctuations are averaged to the mean value. The minimum utilisation rate, taken to be time-invariant, is also used to capture (in a simplified way) the fact that thermal plants have to run at a certain minimum level[6] to ensure stable operation and to avoid a lack of capacity during contingencies, especially in the cases where a thermal unit has to come live from "cold" state (*i.e.* cold start ramp rates are slowest).

[6] *Note that this is not an actual "minimum stable" specification, which would require the model to be solved with mixed-integer techniques not viable for a model of the scale of the CMP model.*

The standard values used for the minimum utilisation rate were 5% for diesel and OCGT plants, 15% for CCGT plants, 20% for coal-fired plants and 70% for nuclear plants. Certain dispatchable renewables, namely biomass and geothermal plants, were also assumed to operate with a 20% minimum utilisation rate. The higher values for CCGT, coal and biomass plants reflect the fact that these plants normally have higher minimum stable operation levels and slower ramp rates than OCGTs.[7]

The second specification was to include unplanned outages at thermal plants, modelled using a derating factor for each power plant's capacity. This limits the output of the plant in modelling its dispatch. This factor was generically taken to be set to the average forced outage rate for each plant (where data were available), and otherwise set to a generic value of 10.5% for reciprocating engine plants and 8% for others. However, for reserve margin purposes, the un-derated capacity was used.

While the approach does not model the temporal dynamics of power plant outages, it factors the outages into the economic considerations of generation expansion.

The fact, that the frequency of unplanned outages can increase with plant ageing, calls for linking the derating factor assumption of each plant to the age of the plant. This approach can be taken up in future model upgrades.

2.3 MODELLING METHODOLOGY UPDATES: POWER GENERATION

In SPLAT-CMP, power generation from thermal and nuclear power plants is modelled in the same way as already described in previous publications on regional applications of the SPLAT model (IRENA, 2018, 2021a, 2023b).

For the CMP development, new state-of-the-art modelling techniques have been developed by IRENA and the IAEA and applied to better represent hydropower, VRE and CSP plants and their spatio-temporal patterns. These are described in this section.

2.3.1 Hydropower plants

Given the enormous variability in climate zones within and between African countries and corresponding patterns in rainfall and river flow, it is of primary importance to model the following two aspects of hydropower generation:

(i) The seasonality in power generation induced by river inflow and constrained by the design discharge of the turbine, as well as mitigating effects that the presence of reservoirs has on this seasonality.

(ii) The sub-daily flexibility that reservoir hydropower plants can provide to support VRE integration, modulated by their seasonal availability.

[7] *The lower values for OCGT are typically observed in literature (i.e. in the results of higher temporal resolution models), although in reality, they depend on various factors specific to each system, in terms of composition and costs/prices.*

All these aspects were modelled at the individual plant level for both existing, committed and candidate plants, using the African Renewable Electricity Profiles (AfREP) hydro database previously published by IRENA for the benefit of the modelling community (IRENA, 2021c; Sterl *et al.*, 2021). This database uses a continental-level river flow dataset in combination with technical information at the hydropower plant level to estimate seasonal CF profiles. The AfREP-hydro database also takes into account existing and potential cascaded dam systems, where multiple (potential) plants are located downstream of each other on the same river; thus, the effects of cascade systems is *a priori* accounted for in the database. For full details on how the AfREP-hydro database was set up, including all relevant equations, the reader is referred to the aforementioned publications.

The data in the AfREP-hydro database were applied to the SPLAT-CMP model as follows. For run-of-river plants, the CF profiles (at monthly resolution) from the AfREP-hydro database, unique to the specific sites of individual hydro plants, were directly applied as availability profiles[8] at the technology level in SPLAT (secondary level in Figure 1).[9] This means that when the river is flowing at maximum rate, the run-of-river hydropower plant is able to generate up to its nameplate capacity (exclusive of any user enforced de-ratings on accounts of ageing, planned and unplanned outages etc).

For reservoir plants, to account for point (ii) above, the reservoir dynamics had to be specifically remodelled in SPLAT. This was done by including two further elements in the model (see Figure 1):

- a river flow technology with its own availability profile, sized in appropriate MW units obtained from maximum river flow estimates available in m^3/s in AfREP-hydro (see formula in Figure 2); and
- a reservoir technology fed by the river flow technology with a certain maximum storage level, sized in appropriate MWyear units obtained from reservoir size available in m^3 in AfREP-hydro (see formula in Figure 2).

The hydropower plant was linked to the reservoir technology by requiring that one unit of production from the plant drains an equivalent unit of storage from the reservoir, and the reservoir was linked to the river technology by allowing the power-equivalent flow of the river to be stored in the reservoir (up to the maximum storage level).

Sizing of both the river and the reservoir technology required an estimate of the corresponding hydropower plant's *design discharge* (m^3/s), which, wherever unknown in the AfREP-hydro database, was assumed to be 50% of the maximum river flow extracted from the modelled continental-level river flow data used for the AfREP-hydro database.[10]

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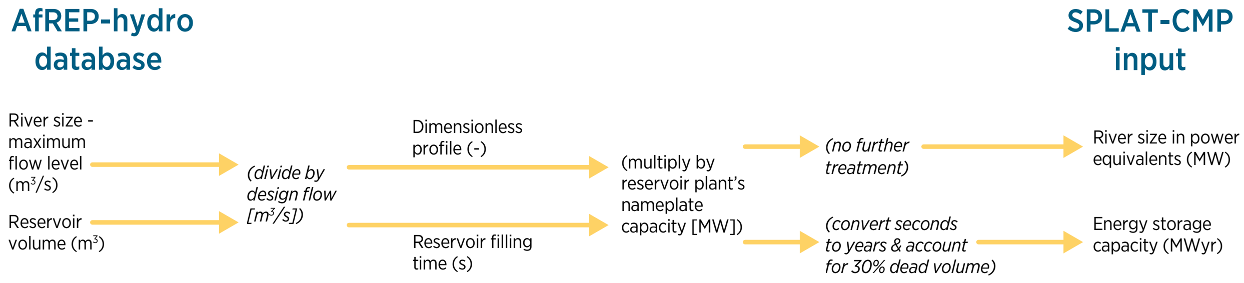
[8] *i.e. flow rates expressed from 0 (no flow) to 1 (maximum flow rate)*

[9] *In theory, if a given candidate plant were to be downrated in capacity, this would increase the overall CF of the plant. The mentioned approach of modelling run-of-river plants does not take this into account, as the CF profiles are linked to a specific assumption of installed capacity. In an ideal case, the potential capacity of the candidate plant would be set by the modeller to a fixed number, so the model could install the plant either at full capacity or not at all, but not "partially". However, this may make the model numerically more difficult to solve.*

[10] *For the same reasons mentioned in the footnote 5, a similar argument applies to reservoir plants.*

Figure 2 The translation of reservoir hydropower data from the AfREP-hydro database to the SPLAT-CMP model



In this way, and following consultation with the involved stakeholders, a total of 601 site-specific hydropower plants (222 existing, 74 committed, 305 candidate) were included in SPLAT-CMP, representing a total of 132 GW of hydropower capacity.

Existing and committed hydropower plants which are (to be) shared between multiple countries (*e.g.* when located on a border river) were split up along with their corresponding river and reservoir technologies and included separately for each relevant country according to the actual capacity allocation.

We note that the AfREP-hydro database includes climate change scenarios for all included hydropower plants under various combinations of RCPs (Representative Concentration Pathways) and SSPs (Shared Socioeconomic Pathways) (Intergovernmental Panel On Climate Change, 2023). Thus, integrating climate change impacts on hydropower resources in the SPLAT-CMP model is straightforward and low-effort.

2.3.2 Solar and wind power plants

While the model allows inclusion of the project-specific solar and wind supply options as indicated in Section 2.1, this resource pool is expectedly limited in size, covering only a small portion of the extensive resource base, of varying attractiveness, scattered across Africa. To sufficiently cover this extensive candidate resource base and its various elements of attractiveness, including the cost of infrastructure needed for grid connection, regional clusters of high-potential sites were included in the SPLAT-CMP model (IRENA, forthcoming; Sterl *et al.*, 2022).

The clusters were based on IRENA's concept of Model Supply Regions (MSRs), which are essentially model-ready "candidate regions" with specific capacity potential, infrastructure costs and generation profiles at the country level.

The Model Supply Region approach

Full details of the scientific basis behind the MSR approach to cluster creation and profile extraction for solar PV and wind onshore is available (Sterl *et al.*, 2022), and the associated datasets are available in open-access form (Sterl *et al.*, 2023). The following sections summarise the parts of the approach that are useful for the SPLAT-CMP model. These sections also present new (and previously unpublished) methodologies for CSP and offshore wind clusters, which are largely based on the same approach. The spatial datasets related to these two technologies are also available in the CMP database (Mwanga),[11] along with those of solar PV and onshore wind.

Characterising the supply options for solar and wind power by cluster in the SPLAT-CMP model, instead of as location-specific individual power plants (the approach used for hydropower), is plausible as (i) VRE potential is much less spatially constrained than hydropower, and (ii) VRE plants have more generic design characteristics than hydropower. Hydropower potential is concentrated in highly specific locations and thus need to be modelled at the individual plant level, with different storage size, river profile, design discharge, etc.; the same constraints do not apply to VRE potential. Nevertheless, the solar and wind resources still require a certain level of spatial differentiation in the model, as the annual production potential and the temporal production patterns can differ between different regions within a country, which means that representing solar and wind power with a single candidate technology within a country is also inadequate.

For most countries, even when excluding unsuitable, prohibited and protected areas, the exploitable potential of VRE tends to cover large swathes of the country's surface area. In SPLAT-CMP, we limited the expansion of VRE technologies to cover at most 5% of a country's surface area (Sterl *et al.*, 2022). To achieve this, the exploitable potential (available as MSRs) was screened for the areas representing the 5% most attractive portions of a country's surface area,[12, 13] defining "most attractive" as "power plants built there would have the lowest expected LCOE". This LCOE (levelised cost of electricity) was calculated considering not only the effects of resource quality (level of solar irradiation and wind speed), but also the distance from existing grid and road infrastructure requiring additional expense for grid and road network buildout.

The resulting set of geospatially referenced regions thus represents a realistic selection of the most interesting locations in each country for constructing power plants while covering possible spatial resource divergences within that country. MSRs can diverge widely in size – some representing large contiguous areas with rather homogeneous resources and no competing land uses, *e.g.* solar resources in desert areas, and others representing small pockets of high but isolated potential, *e.g.* individual hill ridges with high wind speeds. Therefore, the individual MSRs in each country were subsequently grouped into a limited number of clusters with comparable hourly production profiles for model inclusion purposes. While the hourly production profile shape was the only criterion used in the clustering approach, in practice this tended to result in geographically close MSRs being clustered together. This is logical given the typical spatial correlations of generation profiles between sites close to each other (Engeland *et al.*, 2017).

Figure 3 provides a geospatial summary of all MSRs for solar and wind power thus included as candidates in the SPLAT-CMP model. Each of these areas is characterised by its own capacity buildout prospects (MW), unique hourly CF profile, and unique LCOE reflecting resource quality and grid/road buildout requirements. Note that the figure does not show the clusters resulting from grouping MSRs together; however, these data are available in visual format (Sterl *et al.*, 2023).

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[11] *https://cmpmwanga.nepad.org/*
[12] *Or of a country's Exclusive Economic Zone, in the case of offshore wind.*
[13] *As long as this 5% covers potential deemed commercially exploitable (Sterl et al., 2022), which was the case for most countries.*

To account for the ongoing expectations of further cost decreases in VRE and CSP technologies, an approach was adopted whereby the CAPEX for each technology was assumed to start in the base year with a region-specific level (IRENA, 2022a), then decline at a technology-specific average annual rate envisioned by IRENA's World Energy Transition Outlook (WETO) scenario (IRENA, 2022b) till 2030, and subsequently settle onto a technology-specific global average CAPEX assumed by the WETO scenario by the year 2040. This approach was favoured because it gives the flexibility to easily switch from the conservative price path (currently assumed) to a more optimistic path, *e.g.* one where the African market accelerates in price declines to match the assumed future global average CAPEX much earlier than 2040.

Cluster creation for solar PV and onshore wind

According to the adopted approach (Sterl *et al.*, 2022), the solar PV and onshore wind MSRs of each country were grouped into ten, five or two clusters depending on country size (the objective being to have consistent numbers of clusters to include in the SPLAT-CMP model at the country level and to reduce computational requirements). Countries were classified as large (meriting 10 clusters), medium (5 clusters), or small (2 clusters), respectively. Kenya, Algeria, Sudan, Ethiopia, Democratic Republic of the Congo, Egypt, Tanzania, Morocco and South Africa were classified as "large"; Djibouti, Equatorial Guinea, Guinea-Bissau, Lesotho, Eswatini and Gambia as "small"; and all other countries as "medium".

We note that solar PV potential (and thus solar PV clusters) is present in every country, given the widespread resource availability, and thus the SPLAT-CMP model can invest in solar PV clusters in any country. The same does not apply to onshore wind, for which no potential (*i.e.* no MSRs) was identified[14] for Burundi, Equatorial Guinea, Gabon, Guinea-Bissau, Liberia, Rwanda and Sierra Leone, and thus no options for the SPLAT-CMP model to invest in onshore wind clusters exist for these countries.

For all other parameters (*e.g.* exclusion criteria, expected losses) for solar PV and wind clusters, the reader is referred to the source literature (Sterl *et al.*, 2022).

Across all countries, a total of 4.9 TW of candidate solar PV across 272 clusters, and 3.4 TW of candidate onshore wind power across 232 clusters, was included in the model based on the MSR analysis.

Cluster creation for CSP

CSP was deemed only to be able to compete economically with solar PV if it includes thermal storage. Therefore, the model included CSP with six hours of storage as an investment option, but did not include CSP without storage. For each country, the candidate clusters for CSP were derived in a way comparable with solar PV, except using normalised direct normal irradiation (DNI) as a proxy for CF profiles instead of global horizontal irradiation (GHI) (see the equation for solar PV referred to in Sterl *et al.*, 2022), and using a maximum of two clusters per country, not more, to save on the computational burden.

Subsequently, these profiles were mathematically adapted to represent the effect of thermal storage, as follows. It was assumed that a solar CSP plant is designed with a given *solar multiple* (SM), representing the ratio between the theoretical power that could be generated from the entire solar collector field on the one hand, and the steam turbine capacity, which places an upper cap on this power, on the other hand. If this ratio

[14] *Based on the various assumed land exclusion criteria (Sterl et al., 2022), including a minimum threshold for resource quality of 6 m/s annual average wind speed at 100 m height.*

is larger than one, it is assumed that the "excess" insolation is used for thermal storage until night-time, when the stored heat is used to evaporate water to let the steam turbines of the plant operate at maximum output for as long as the stored power lasts (effectively allowing the plant to function as baseload at night-time).

For the SPLAT-CMP model, the CSP profiles were modelled assuming a solar multiple of 2.0 and a maximum storage duration of six hours, with storage dispatch starting at 5pm local time. We assumed annual losses of 4% on accounts of planned and unplanned outages, similar to the assumption for solar PV (Sterl *et al.*, 2022), process losses (radiant energy to heat, heat to power) of 4%, and storage losses at 4.2% per hour of stored energy (IRENA and LBNL, 2015).

Given the geographic disparity in DNI levels (as opposed to GHI, which is much more equally distributed), not every country boasts realistically exploitable CSP potential. No CSP MSRs were identified[15] for Rwanda, Equatorial Guinea, Gabon, Ghana, Liberia, Republic of Congo, Rwanda, Sierra Leone and Togo.

Across all countries, a total of 2.3 TW of candidate CSP capacity across 82 clusters was included in the model based on the MSR analysis.

Cluster creation for offshore wind

Offshore wind MSRs were obtained identically to onshore wind profiles as described in the source literature (Sterl *et al.*, 2022), with the following adaptations. First, two types of offshore wind power plant, floating and fixed, were considered based on seabed depth – floating for regions with an average depth of 50 m or more (up to 800 m, beyond which regions were excluded from consideration), and fixed for shallower regions (with floating wind farms having the higher CAPEX). Second, grid connection costs were differentiated between the offshore part (a transmission line from the MSR to the nearest point on the country's shore) and the onshore part (a transmission line from the landing point on the shore to the nearest transmission grid), with the offshore transmission infrastructure costing more per kilometre than the onshore infrastructure. Third, the area considered for each country corresponded to that country's Exclusive Economic Zone (EEZ), and the selection of MSRs for model inclusion corresponded to the most attractive 5% of the EEZ's area.

Offshore wind MSRs were clustered into two clusters for each country,[16] independent of its EEZ area, to reduce the computational burden.

The number of countries with identified offshore wind potential was relatively limited. Clusters of offshore wind potential were only available for a selection of non-landlocked countries, namely Algeria, Angola, Djibouti, Egypt, Eritrea, Somalia, Madagascar, Mauritania, Morocco, Mozambique, Namibia, Senegal, South Africa, Sudan and Tunisia.[17]

Across these countries, a total of 470 GW of candidate offshore wind power capacity across 28 clusters was included in the model, based on the MSR approach.

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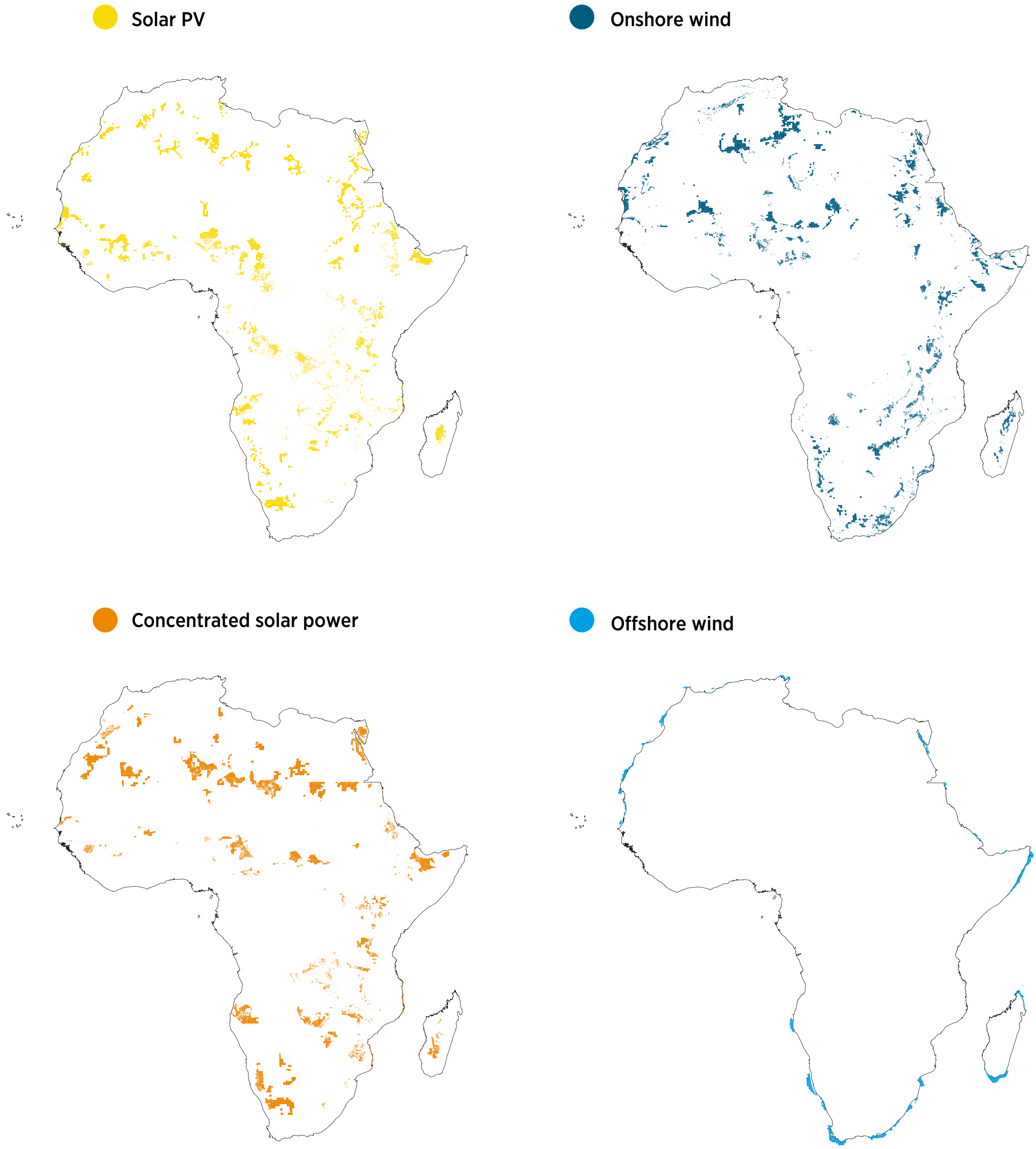
[15] *Based on the various assumed land exclusion criteria described in the reference literature (Sterl et al., 2022), including a minimum threshold for resource quality of 4 kWh/m2/day annual average DNI.*

[16] *In clustering offshore wind MSRs, individual clusters might include both areas suitable for fixed turbines and areas suitable for floating turbines. The "majority rule" was adopted to allocate the structure type (fixed/floating) to a cluster and thus the costs.*

[17] *Based on the various assumed land exclusion criteria described in the reference literature (Sterl et al., 2022), including a minimum threshold for offshore resource quality of 7.5 m/s annual average wind speed at 100 m height.*

Figure 3: Geospatial overview of the areas for solar PV, CSP, onshore wind and offshore wind power generation included in the SPLAT-CMP model through IRENA's MSR approach



Notes: The shown areas represent the 5% most attractive locations (in LCOE terms, including grid extension costs) (as a percentage of a country area, or – in the case of offshore wind – of a country's EEZ) for generating electricity from the respective plant types. This figure shows only the MSRs, not the clusters into which MSRs were grouped by country.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

2.3.3 Geothermal power plants

Candidate geothermal power plants were included in a spatially distinct manner, similar to the approach for hydropower introduced above. During the conception of SPLAT-CMP, AUDA-NEPAD commissioned a study to identify the most promising geothermal development areas across countries straddling the East African Rift, with location-specific maximum deployable capacity (EU GTAF, 2023a).

In this way, and following consultation with the stakeholders involved, a total of 28 candidate geothermal plants across Djibouti, Ethiopia, Kenya, Tanzania and Uganda were included in SPLAT-CMP, representing a total of 12 GW of capacity.

2.3.4 Note on discount rate

In the MESSAGE modelling framework, a single "discount rate" parameter is used to serve two distinct purposes:

(i) To calculate the annualised investment costs associated with the deployable supply side infrastructure (generators, interconnectors, batteries etc.), from respective assumptions on overnight capital cost, life period and the project construction period. The annualised cost is assumed to incur each year during the project life period excluding the first year of operation. Here, the use of discount rate parameter corresponds to the concept of "hurdle rate" as typically used in project capital budgeting exercises. Hurdle rates are unique to individual technology markets but given the societal purview of MESSAGE's discount rate parameter, making distinctions on technology basis is not possible.

(ii) To bring the annualized capital costs and other various operational costs associated with the energy system technologies, incurred across the study period, to a common base year as the discounted sum. This discounted sum represents the objective function of the model and is subjected to optimisation (minimisation).

The CMP stakeholders agreed on a 10% discount rate, the default discount rate offered in the SPLAT-MESSAGE framework originally adopted from the 2011/12 West Africa Power Pool master plan and the 2014 East African Power Pool master plan. Compared to IRENA's recent survey of cost of financing for renewable power (IRENA, 2023c), which puts most of the WACC observations – taken across the globe and including several African countries – below 9%, CMP's discount rate assumption is rather high and reflects the relatively higher challenges faced in securing capital resources by most African countries.

Discount rate parameter is an important modelling parameter that can significantly influence the model results. Higher discount rates negatively affect the prospects of future generation assets that have large upfront capital requirements and low operating costs *i.e.* most of the renewables that don't have ongoing fuel expenses, resulting in very low operating costs.

2.4 MODELLING METHODOLOGY UPDATES: CROSS-BORDER POWER TRANSMISSION

Given the focus of the CMP process on the buildout of continental-level infrastructure for integrating countries' power systems into a continental grid, it was of prime importance for the SPLAT-CMP model to have a good representation of cross-border power transmission. This section describes how transmission options were modelled, both between African countries and from Africa to other continents.

2.4.1 Interconnectors between African countries

As mentioned above in Section 2.1, cross-border power transmission is possible in SPLAT-CMP through existing, committed and candidate (user defined or pre-loaded generic) interconnectors. Here, given that parameters such as maximum capacity and costs for existing and committed interconnectors are assumed known (and, in any case, do not affect the optimisation), the pre-loaded generic "candidate" category (interconnectors between any possible pair of neighbouring countries on continental Africa, of which there are 106) required the most in-depth modelling work.

Given that the SPLAT-CMP model framework does not explicitly include parameters representing the length of transmission lines, these had to be implicitly included in the CAPEX (in terms of USD/MW of transmission line capacity deployed by the model) for each separate generic interconnector. This was done through a mathematical approach explained below. The approach combines four distinct characteristics of interconnectors:

(i) A transmission line's required voltage level depends on the length of the line, with longer distances requiring higher voltages to keep resistance losses low, and higher voltage lines being more expensive per kilometre.

(ii) Higher-voltage lines can reliably transmit more power than lower-voltage lines (over a given distance).

(iii) Longer lines can reliably transmit less power than short lines (at a given voltage).

(iv) The costs of interconnector lines across the same distance tend to be higher in more difficult terrain such as mountains than in flatlands.

The general challenge was thus to come up with representative costs in USD/MW that would take into account the distance covered and voltage required on each generic interconnector.

The approach starts by assessing the probable distance that would need to be covered by an interconnector linking two countries' national grids. This was done by calculating the shortest distance between two countries' transmission grids, obtained from the GridFinder dataset (Arderne *et al.*, 2020). The list of results on a country-pair basis is given in the Appendix.

Subsequently, the appropriate voltage level and the corresponding type of interconnector (AC, HVAC or HVDC) were determined from this distance according to the data in the lookup Table 2. Each voltage category was also assigned a unit cost per kilometre (USD/km) based on transmission line data obtained from the Southern African Power Pool (SAPP) (Table 2). These data provide the numbers needed to quantify element (i) above.

Table 2 Translation of generic interconnector distance categories to voltage level categories as used in the SPLAT-CMP model setup

Distance category (km)	Default voltage levels (kV) and type	Unit line costs (USD 10^3/km)	Converter + transformer costs (USD 10^3/MW)
0-120	66 (AC)	130.3	45.8 (transformer)
120-240	132 (HVAC)	175.2	
240-480	220 (HVAC)	208.2	
480-600	400 (HVAC)	392.2	
600-800	500 (HVDC)	466.4	142.8 (converter + transformer)
> 800	600 (HVDC)	525.8	

Notes: AC = alternating current; HVAC = high-voltage alternating current; HVDC = high-voltage direct current. The voltage level as a function of distance was inspired by (Minai and Khan, 2012), but with two additional categories for HVDC added for distances > 600 km. The converter and transformer costs were based on (Barnes *et al.*, 2022).

The total power transfer capacity (excluding losses) of a line at a given distance and given voltage level can be calculated by multiplying its surge impedance loading (SIL),[18] which quantifies the effect of line voltage on a line's capability to reliably transmit a given level of power (see element (ii) above), with its line loadability (LL),[19] expressed as a percentage of SIL, which quantifies the effect of line length on a line's capability to reliably transmit power (see element (iii) above) (Martin *et al.*, 2017). Both SIL as function of line voltage and LL as function of line length (expressed through the so-called St. Clair curve or universal line loadability curve) were derived from literature (Kundur, 1994); the functions applied for SPLAT-CMP are shown in Figure 4.

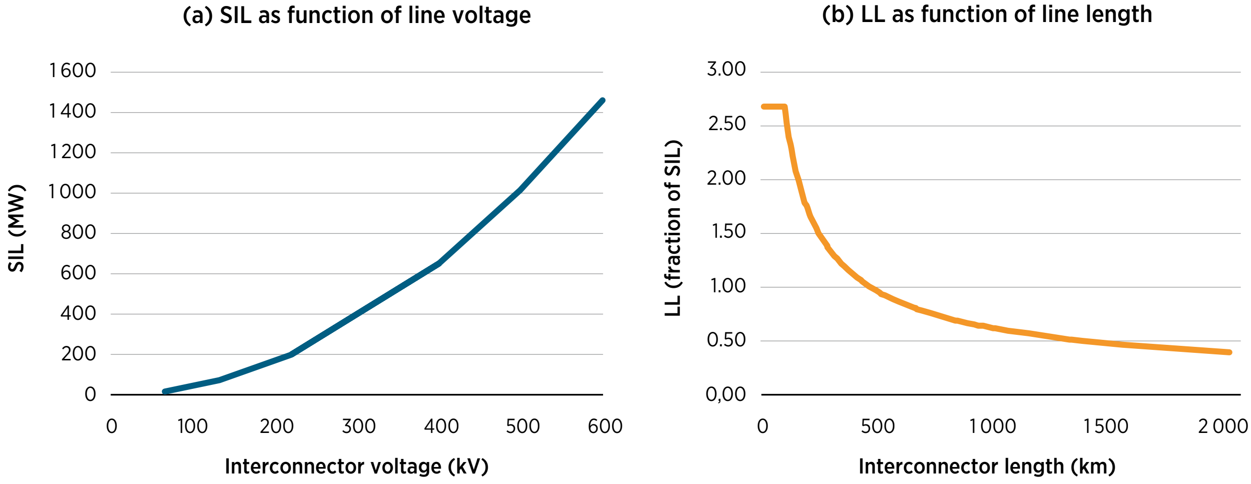
For each generic interconnector, characterised by its own interconnector length and interconnector voltage (see Table 2), the product of SIL and LL could thus be calculated, providing the power transfer capacity in MW excluding losses.

The costs in USD/MW were subsequently calculated as follows. First, the unit costs per km (see Table 2) were multiplied with the line length, obtaining total costs in USD. Subsequently, converter costs (for HVDC) and transformer costs (for AC, HVAC and HVDC) were added; these were obtained by multiplying the costs per unit of transfer capacity for AC, HVAC and HVDC categories (see Table 2), obtained per category from the literature (Barnes *et al.*, 2022), with the previously found power transfer capacity. Last, the sum of costs was divided by the power transfer capacity to obtain a number in USD/kW.

As a final step (see element (iv) above), the effect of terrain difficulty on unit cost of constructing interconnectors was considered. To this effect, a "terrain multiplier" factor was applied to all unit costs in USD/MW found in the previous step. We have considered terrain multipliers with discrete values of 1.0, 1.5 and 2.0, inspired by Wei *et al.* (2017), with 1.0 referring to flatlands, 1.5 referring to hilly or somewhat mountainous terrain, and 2.0 referring to highly mountainous regions as well as to otherwise hostile terrain such as swamps, dense rainforests and uninhabited deserts lacking transport infrastructure and water supply. The assignment of terrain factors to generic interconnectors was done according to expert judgement and remains somewhat subjective. A list of the terrain factors considered is provided in the Appendix. The resulting

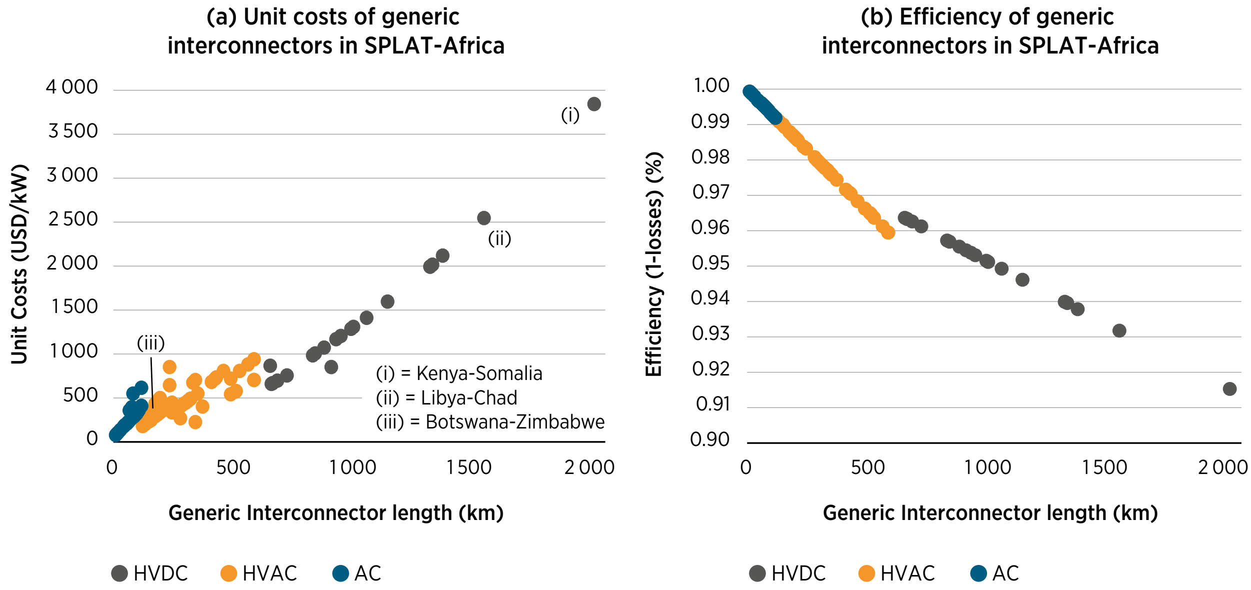
18 *SIL represents the loading level at which the line attains self-sufficiency in terms of reactive power (i.e. no reactive power into or out of the system).*
19 *LL represents limiting factors for line loading due to thermal limits (at short distances), voltage drop limitations (at medium distances), and steady state stability (at long distances).*

Figure 4 (a) Surge impedance loading (in MW) as a function of interconnector voltage level, and (b) line loadability (as a fraction of surge impedance loading) as a function of interconnector length



Notes: LL = line loadability; SIL = surge impedance loading.
Source: Functions obtained from (Kundur, 1994).

Figure 5 (a) Generic interconnector unit costs as used in SPLAT-CMP. (b) Efficiency of generic interconnectors as used in SPLAT-CMP, including line losses and converter losses



Note: Each point in the graphs represents one potential generic interconnector between neighbouring African countries. Three examples of generic interconnectors are highlighted in (a).

values of investment costs in USD/kW, which were directly used in the SPLAT-CMP model to represent generic interconnectors, are shown graphically in Figure 5(a). The results on a country-pair basis are also given numerically in the Appendix.

The relative losses on interconnectors were quantified by summing up line losses and converter losses and dividing these by the previously identified transfer capacity. Loss rates for lines and converters were obtained by voltage category (AC, HVAC, HVDC) from Barnes *et al.* (2022) and are shown in Figure 5b, as well as numerically in the Appendix.

Thus, in summary, the SPLAT-CMP model has 106 generic interconnectors to choose from in the optimisation; and as shown by Figure 5, the longer the interconnector distance, generally, the more expensive and less efficient the interconnector. Especially at high interconnector lengths across difficult terrain (*e.g.* those that would have to cross the Sahara desert, between countries such as Libya and Chad, see Figure 5a), this resulted in these interconnectors becoming unattractive in most conceivable model scenarios, as one would expect.

2.4.2 Interconnectors between Africa, Europe and Asia

The power systems of countries outside Africa that have existing and/or planned interconnections to African countries are not modelled explicitly in SPLAT-CMP. Instead, these interconnections are modelled in a simplified manner on an import/export price basis (IRENA, 2023b). Historical hourly marginal prices in European countries from the year 2019 were used for connections between North Africa and European countries (Italy, Spain, Portugal and Greece). Due to the lack of such hourly data for Jordan (interconnected with Egypt) and Saudi Arabia (to be interconnected with Egypt), annual prices are used for these exchanges. The model will decide on the moments of export/import.

During the optimisation process, the decision will be made to export if the marginal cost of available electricity is lower than outside the continent, and to import if the marginal cost is higher than outside the continent. Overall imports/exports in any time slice are logically limited by the maximum transfer capacity of each interconnector, which acts as a proxy on a limit in terms of import/export share as a percentage of total demand in a year.

The interconnectors considered in the model are either existing or identified projects of interconnection. These included Morocco–Spain, Morocco–Portugal, Tunisia–Italy, Egypt–Jordan, Egypt–Saudi Arabia and Egypt–Greece. No generic interconnectors between Africa and Europe and/or the Middle East were included, *i.e.* the model does not expand interconnections out of Africa beyond what is already existing, committed and planned (candidate).

2.5 MODELLING METHODOLOGY UPDATES: REPRESENTATION OF STORAGE

Two electricity storage technologies were considered in the SPLAT-CMP modelling: closed-loop (off-river) pumped-storage hydropower plants and battery storage plants. As shown in Figure 1, pumped-storage hydropower plant candidates were site-specific (just like regular hydropower plant candidates), based on the specific support study on pumped-storage hydropower as part of the CMP process (EU GTAF, 2023c) as well as inputs from country representatives during capacity-building sessions. Battery storage schemes, in contrast, were modelled as generic.

In terms of the modelling, these two technologies are represented differently from regular hydro storage using dams. Hydropower dams regulate the inflow of water and can enable seasonal regulation of water flow and electricity generation. Conversely, both pumped-storage hydro and batteries are mostly used for daily regulation of electricity generation, consuming electricity when surplus or cheap electricity is available and generating when there is a lack of generation or in preference to more expensive generation options at a later point, usually in the order of hours later.

In SPLAT-CMP, the pumped-storage hydropower and batteries were modelled to consider the following aspects:

- Daily operation: The storage plants are limited to daily operation and cannot be used to perform seasonal storage. Appropriate constraints are included for each 'time slice' (term explained in Section 3) to prevent seasonal storage.
- Power/energy volume ratio: A ratio is defined between the total capacity of the storage and the volume of energy that can be stored in the batteries or the pumped-storage hydro. For example, a four-hour battery is a battery whose stored volume of energy cannot exceed four hours of battery dispatch at full capacity. Four-hour batteries were used as the default battery type in all countries.
- Losses: Each cycle of charging/discharging is associated with a specific loss factor (10% for batteries, 25% for pumped-storage hydro).

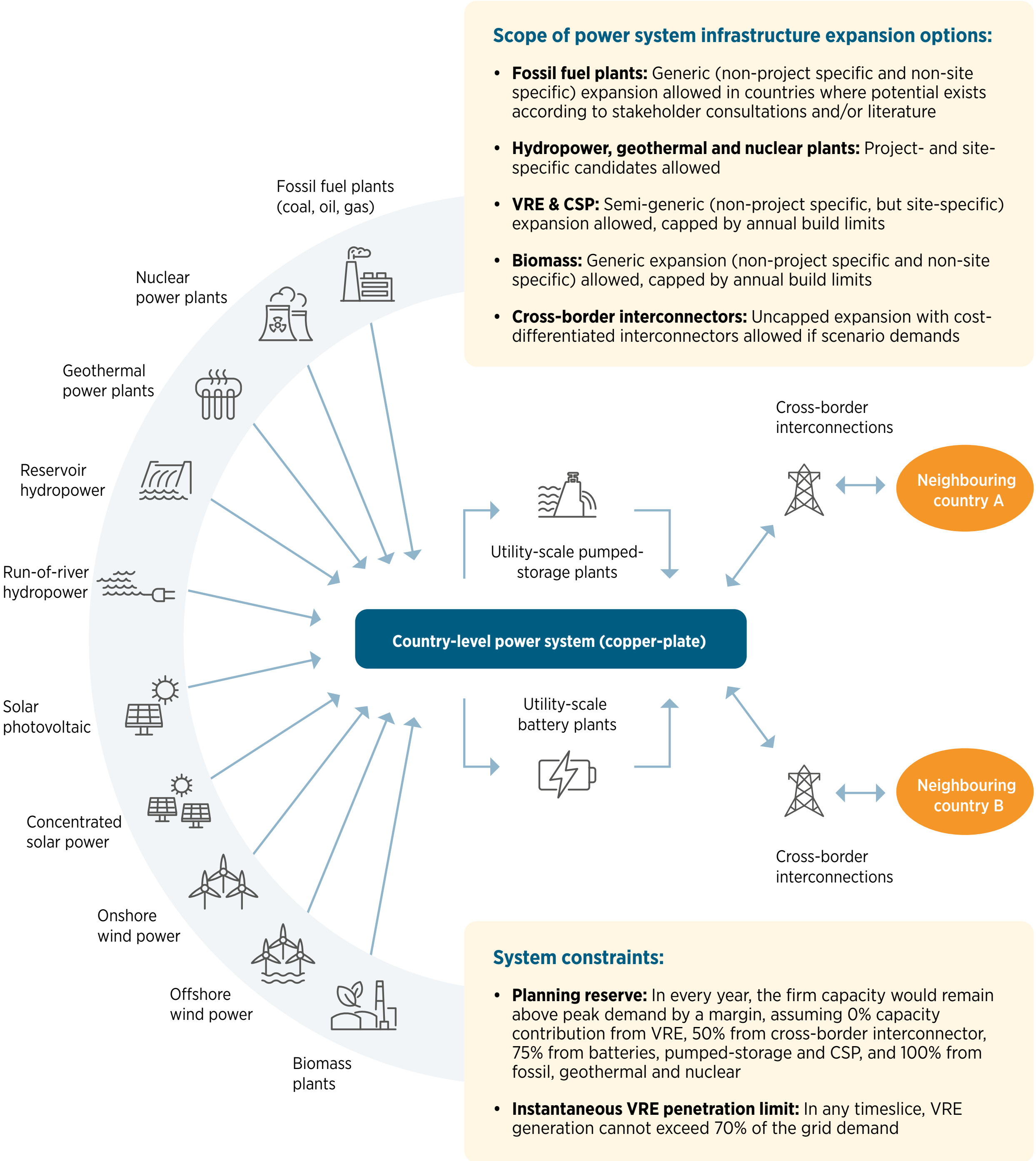
The costs for pumped-storage hydropower plants and battery plants used in SPLAT-CMP were based on (NREL, 2021), as already in previous work by IRENA (IRENA, 2023b).

2.6 SUMMARY

Section 2 of this report has described multiple elements of SPLAT-CMP model design, including (i) the representation of power generation technologies, cross-border interconnectors, and storage, as well as (ii) the scope of generic expansion options for each different technology, and (iii) several technology-, country- and continent-level constraints.

A graphic summary of these elements is provided in Figure 6.

Figure 6 Graphical representation of the various modelling elements of the SPLAT-CMP model



3. STRATEGIES FOR RUNNING SPLAT-CMP MODELS

Through the MESSAGE framework, the SPLAT-CMP model allows a flexible definition of the modelling regions and time resolution. It is possible to generate an hourly resolution model for both the individual countries and the whole continent. In the case of the individual country models, it is possible (feasible) to solve the underlying so-called "mathematical optimisation problem" at an hourly resolution, often but not always using the commercial solvers. Conversely, in case of the continent-wide model – with coverage of 48 countries, a 23-year modelling horizon and more than 6 000 separate technologies in its largest form – the hourly optimisation problem becomes huge and impossible to solve with the common commercial solvers and computational resources. The elaborate representation of cross-border interconnections in the model makes the optimisation problem especially more complex to solve.[20]

Consequently, in practice it is infeasible to run the SPLAT-CMP model at hourly resolution and some aggregation of the time resolution, so-called "time slicing", is necessary. During the CMP modelling, the continent-wide model was routinely run at 10 time slices with an average solve period of 45 minutes in its largest form, *i.e.* a transition scenario that entailed a maximum number of generic cross-border interconnectors. Several times, the same case was also run at 36 time slices with an average solve period of roughly 2 hours. The 10 and 36 time slice configurations involved three seasons entailing one day each and 3-4 and 12 time slices per day respectively. Table 3 gives an indication of the size of the continental model generated at different time resolutions using the SPLAT-CMP model.

Table 3 Summary of how the number of variables, constraints and non-zero matrix elements change with the number of time slices in the SPLAT-CMP model used for the CMP

Number of time slices	Number of variables	Number of constraints	Non-zero elements
10 (low-resolution version with three seasons and three to four daily time slices)	~1 million	~1.5 million	~18 million
36 (three typical seasons with 12 daily time slices each)	~4 million	~5 million	~60 million
288 (each month represented with one typical day at hourly resolution)	~33 million	~41 million	~500 million
8 760 (full hourly)	~1 000 million	~1 200 million	~15 000 million

[20] *This is because the resulting constraints carry many variables, which eventually result in a problem matrix less sparse than a single country model, and non-zero elements outside the diagonal band become more present. This applies when we add spatial nodes and exchanges between nodes (interconnections do that) and timesteps and exchanges between those timesteps (storage does that).*

Given that there is no intrinsic limit on the maximum count of time slices that can be defined in SPLAT models, it is up to the user to determine the appropriate time resolution based on the scenario requirements and the computational resources at its disposal. With the MESSAGE framework, the whole year can be defined flexibly with any number of seasons, the underlying day types in each season and any number of time slices per day. With the SPLAT interface, the sub-annual assumptions on different modelling parameters (such as load or the CF of renewable generators) can be prepared in accordance with the designed time slices.

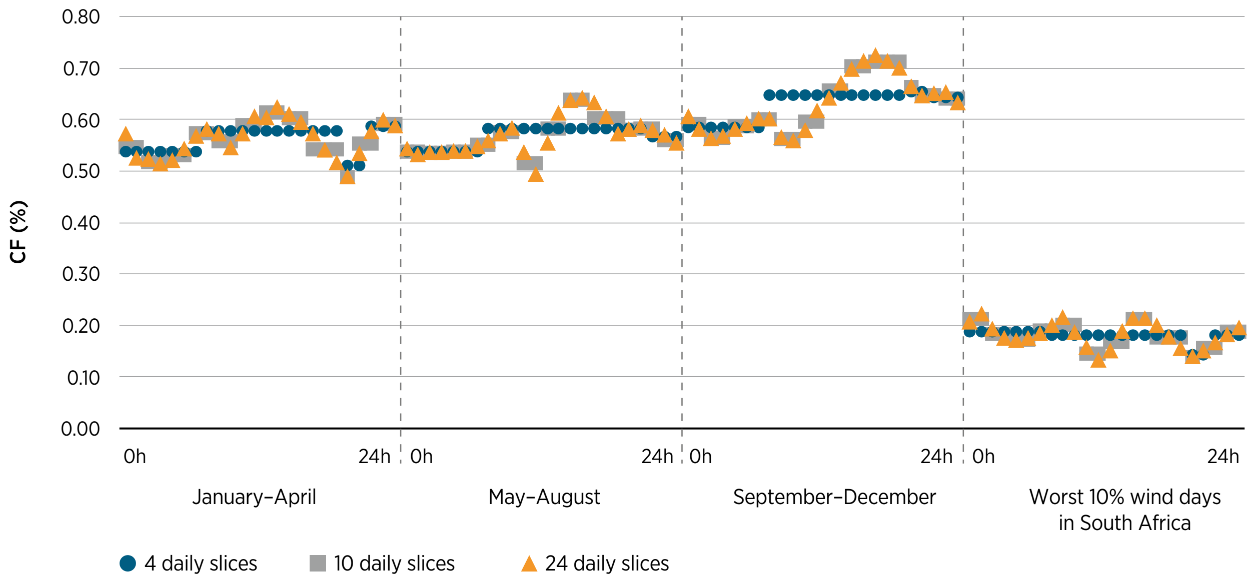
An important element of SPLAT's time slice defining methodology is the country-level preservation of peak load hours. This approach works as follows. First, the hour of the year with maximum demand is identified at the country level. Second, after performing the initial averaging across time slices, the day type under which the hour of peak demand falls is identified, and energy is shifted into the aggregated peak time slice, such that the model "sees" the actual peak in the aggregate profile definition. Thus, slightly more energy is allocated to that time slice than before. To avoid the total amount of energy across all time slices being inconsistent with the original time series, the "extra energy" added to the peak time slice is subtracted from the other (non-peak) time slices in proportion to the original shares of energy contained in each of them (computed by averaging). This approach tends to work well, especially when the temporal resolution of the time slices used is relatively high (so that the peak demand automatically falls in a "short" time slice representing, for example, just one hour).

We note that the traditional time slice approach, like the one described above, tends to work well for representing the variability of power demand, hydropower and solar PV, as the main variabilities of these parameters play out on hourly and seasonal timescales (IRENA, 2017). For wind, the situation is somewhat different as it is also variable on a day-to-day and week-to-week time scale (Engeland *et al.*, 2017).

Consequently, the traditional time slicing approaches tend to underestimate the variability of wind power, and especially the occurrence of prolonged "wind droughts", as these tend to be averaged out – since time slicing approaches usually presuppose that the main variabilities to be represented are hourly and seasonal. The result is that wind power typically appears to be a more stable power source in time-sliced results than it actually is, *i.e.* the wind variability is under-represented. In some cases, this can lead to wind power almost appearing as "baseload" technology, leading to unrealistic model results.

This is illustrated in Figure 7, where the time slice-wise CF of South African MSR cluster #2 (see Section 2.3.2) is shown for three cases (4, 10 and 24 daily time slices) across three seasons of four months each, in comparison to a "hypothetical" season consisting of the 10% worst wind days of the year. These worst wind days have an average CF less than one-third of the seasonal average CF; clearly, power system planning needs to take such events into account and working only with the three "regular" seasons would lead to model results overestimating the "firmness" of wind power.

Figure 7 The CF per time slice of South Africa's onshore wind MSR cluster #2



Note: CF shown across three four-month seasons with 4 (circles), 10 (squares) and 24 (triangles) daily time slices each, as compared to a hypothetical season representing the 10% worst wind days of the year.

Running the SPLAT-CMP model at hourly resolution would principally solve the issue of under-representation of wind variability, but as mentioned earlier, it is computationally not practical. In this context, Box 3 provides some additional methods under consideration to address the issue in the SPLAT-CMP model.

Box 3 Potential methods to investigate wind variability aspects in the SPLAT-CMP model for future assessments

Implementing hypothetical "weak wind" seasons to represent wind stochasticity

One of the major aspects of wind variability that remains uncaptured by classical seasonal time slices are the "wind droughts" that can last from days to weeks. One possible way to address this in capacity expansion models, without unduly burdening computational requirements, is to explicitly distinguish between periods of low and high resource availability, inspired by a range of researchers (Helistö *et al.*, 2020; Nahmmacher *et al.*, 2016; Poncelet *et al.*, 2016). This allows the better approximation of the statistical properties of wind across time slices, for instance addressing their load duration curves.

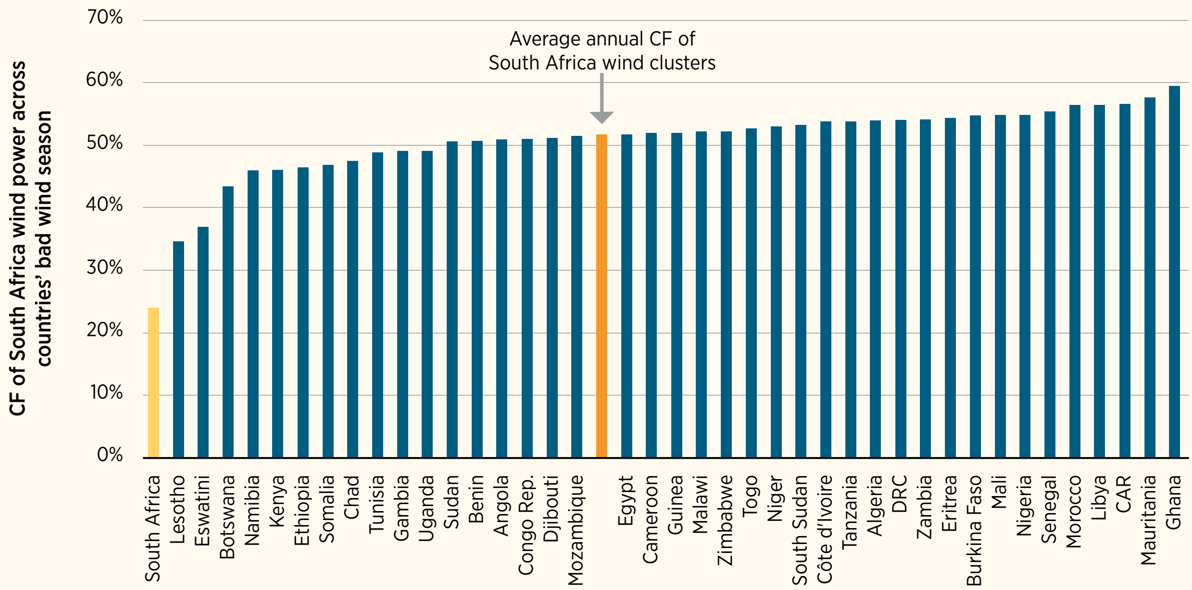
For example, a simple way of increasing the statistical representation of wind properties would be to introduce a fourth "hypothetical" season in the model, covering the "worst" wind days of the year (*e.g.* the 10% of days with the lowest wind speeds) to allow the model to better assess the amount of firm capacity needed to cover bad wind periods. This season would be hypothetical in that it represents a non-chronological set of days. (One could also define such a "weak wind" vector separately for each regular season included in the model for further precision.)

The main challenge in this regard appears when running scenarios at the continental level, as there is no "bad wind season" at the continental level. When expanding the geographical scope beyond country borders, the spatial correlation length of wind vectors is quickly surpassed, and it is no longer possible to identify a clear "bad wind season". In other words, Africa is larger than the weather systems.

Box 3 Potential methods to investigate wind variability aspects in the SPLAT-CMP model for future assessments (continued)

This is graphically illustrated in Figure 8, which shows the average wind power CF of South Africa's ten MSR clusters (each one given equal weight) across the country's bad wind season (10% worst days), as compared to the average wind power CF of South Africa's ten MSR clusters based on the bad wind season of every other African country. Clearly, a weak wind season has no meaning beyond a country's borders: from the point of view of South Africa's wind power profiles, Cameroon's weak wind season represents merely a random collection of days.

Figure 8 Effect of spatial spread on weak wind seasons



Notes: CAR = Central African Republic; DRC = Democratic Republic of the Congo; Congo Rep. = Republic of the Congo. The average onshore wind CF of South Africa's 10% worst wind days (determined by taking the aggregate onshore wind profile of all of South Africa's MSR clusters with equal weight) is 23%, but when redoing the calculation based on the 10% worst wind days of any other country, the CF approaches the annual average, indicating that hypothetical "bad wind seasons" are only meaningful at the individual country level. This may pose challenges when running time-sliced models at continental level.

Importantly, this does *not* mean that wind droughts would have no impact on continentally integrated power systems, because given transmission constraints between countries and within national systems, it cannot be guaranteed that other regions would automatically "jump to the rescue". For continental scenarios, therefore, one approach could be to first run individual country scenarios including each country's individual weak wind season and using the end result (in terms of wind power penetration in the power mix) to inspire country-level constraints in the continental run. Since cross-border transmission can somewhat mitigate weak wind days, the country-level runs do not have to necessarily provide a strict upper cap on wind power penetration for continental runs, but they could serve to benchmark upper limits that are slightly higher.

Resource-based slicing to prioritise the representation of wind variability instead of time-based slicing

Arguably, for systems that may have high wind power penetration, the time slice approach focusing on "average" days across multi-month seasons is an inefficient use of computational time, since it deprioritises the representation of stochastic fluctuations in wind production as compared to representing typical sub-daily patterns. Depending on the climate zone, such sub-daily patterns certainly exist and affect system planning (Sterl *et al.*, 2018); yet, alternative methods have been proposed that shift this prioritisation fully towards representing the variability of wind and the (lack of) correlation between wind generation in different regions.

Box 3 Potential methods to investigate wind variability aspects in the SPLAT-CMP model for future assessments (continued)

In such an approach, called "resource-based slicing", time slices are defined according to VRE generation rather than by season or time of day. For instance, a slice could be defined as representing "high wind, low solar, high demand", aggregating all hours of the year to which this description applies irrespective of the chronology (Lehtveer *et al.*, 2017).

The major advantage of this method is that it allows us to represent the variability characteristics of VRE with a much smaller number of time slices than the season/time-of-day-based time slicing would require, thus lowering computational requirements substantially. As a consequence, it also allows us to better estimate the need for dispatchable generation and flexibility, as well as the effects of curtailment, as compared to traditional time slice methods. However, one potential drawback of this method is that it loses chronology, which may hinder the representation of battery storage dynamics as well as of solar–wind power complementarity on sub-daily scales (Lehtveer *et al.*, 2017; Norvaiša *et al.*, 2021).

Again, challenges related to defining time slices applicable to the entire continent may also exist with this method, just as they might for the "weak wind season" method described above.

Feedback from hourly dispatch models soft-coupled to capacity expansion models

A third option consists of soft-coupling capacity expansion modelling results (*i.e.* the 2040 generation mix and interconnector capacities from SPLAT-CMP) with an hourly dispatch model/tool, such as the IRENA FlexTool (IRENA, 2020). Such investigations can assess the performance of the identified supply mix during different parts of the year across different individual countries, groups of interconnected countries, or even the whole interconnected continent if computational resources permit.

In this process, the time slice-based capacity expansion optimisation and hourly-scale dispatch optimisation happen separately, but inform each other. This prevents having to run hourly scale capacity expansion optimisation (computationally too expensive at the continental scale), while still allowing us to reveal discrepancies between SPLAT-CMP model outputs at the time slice level and FlexTool outputs at an hourly resolution in terms of additional dispatchable capacity needed to cover wind droughts. For instance, one could take a selected year of SPLAT-CMP outcomes in terms of installed capacity, and run FlexTool simulations with that same installed mix (assumed as being fixed) to see which *additional* investments FlexTool suggests *for that year* (Cannone *et al.*, 2023; Daka and Farzaneh, 2023). Subsequently, any additional investments suggested by FlexTool could be forced into the SPLAT-CMP scenario in the same year, before re-running said scenario; this process could be repeated (for multiple selected years) until (satisfactorily close to) convergence (IRENA, 2017).

We note that FlexTool assessments coupled with time-sliced capacity expansion modelling will provide insights beyond investigating the effect of wind droughts, as full hourly simulations also address other problems related to (for example) underrepresentation of sub-daily variability of VRE and demand in a time slice approach.

Approaches to using iterative runs between capacity expansion models with time slices and hourly dispatch models feeding back into the capacity expansion scenarios have been demonstrated in, for example, OSeMOSYS-FlexTool soft-couplings for selected African countries (Cannone *et al.*, 2023). Future work on SPLAT-CMP is likely to include a comparable coupling.

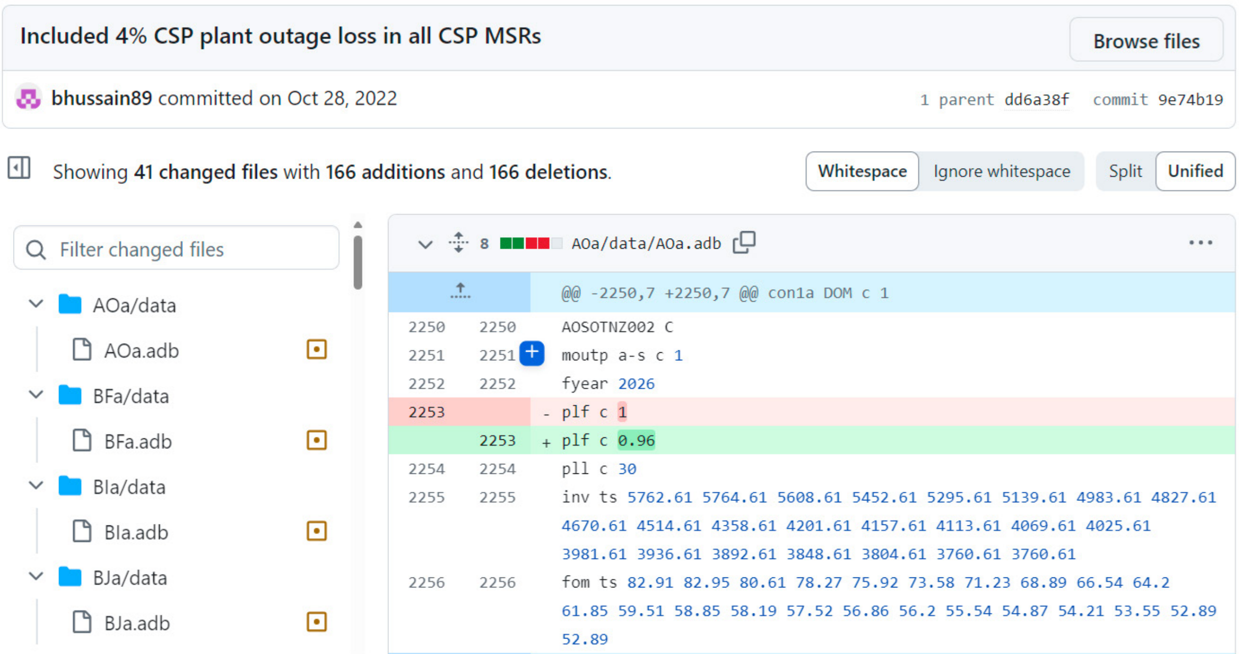
4. MODEL VERSION CONTROL

The joint effort invested in creating the SPLAT-CMP model, which required close collaboration between modelling teams spread across various organisations (AUDA-NEPAD, IRENA, IAEA, African power pools, EU GTAF), necessitated a robust method for ensuring model version control. The file infrastructure behind the MESSAGE model (see Section 1), which is largely based on files in *.txt* (or similar) format, allowed for such version control using a Git repository.

The overarching folder containing all files for the SPLAT-CMP model was hosted in an online Git repository and cloned into the corresponding MESSAGE model folder on the local machines of all members of the modelling teams involved in the project. Whenever any change in model parameters was undertaken by any member of the modelling team, this member could (if satisfied with the change) commit and push this change to the online repository, allowing all other team members to pull it to their local folder and running the model anew with the change in effect.

The *.txt*-based format of the background files for MESSAGE allowed a straightforward visualisation of the changes undertaken at each step, such as in the example shown in Figure 9.

Figure 9 Screenshot from the SPLAT-CMP repository on github.com



Notes: Screenshot shows a commit made by one of the team members. The line highlighted in green (added) and red (deleted) shows the difference between the model file after and before the commit. In this case, a 4% outage loss was added to all solar CSP model supply regions (see Section 2.3.2) by changing the "plf" (plant factor) parameter from 100% to 96% in the commit for all countries.

This approach also allowed us to create different branches off the main model development, providing the modelling team freedom to test out various new model elements without unduly affecting the simultaneously ongoing development of the main model branch.

The experience of working on the SPLAT-CMP model in this way, with a team of 10-20 people spread out over various continents, has been highly positive. We therefore recommend that any collaborative energy modelling effort with a larger team considers using a software setup that allows easy tracking of changes and proper version control. In particular, for MESSAGE-based models, the use of the Git software was found to be user-friendly and accessible to newcomers in the modelling team.

5. POSSIBLE FUTURE AREAS OF WORK/STRATEGIES FOR IMPROVEMENT

Thanks to the commendable collaborative efforts of the CMP stakeholders, the SPLAT-CMP model already represents a tool ready to inform a continental-scale generation and cross-border transmission expansion strategy. Now, to further improve and broaden its decision-support and policy-informing capabilities in future, several enhancements are described below – as highlighted during the various consultations performed in the first CMP exercise.

The first improvement pertains to introducing more granularity in the transmission line expansion options within a country and including multiple nodes, especially for particular large countries. For instance, the Democratic Republic of the Congo in reality has several independent grids that could be allocated to different African power pools (Central, Eastern, Southern). In future versions of SPLAT-CMP, it would make sense to represent such country cases as a number of different subnational entities that require their own mutual interconnections. More generally, higher node representation has been shown to have generic benefits as single-node resolution may tend to underestimate energy and storage needs and can lead to increased curtailment (Frysztacki *et al.*, 2023). Any efforts to increase in-country resolution across the continent calls for more information on national grids and spatially resolved information on existing plants and future supply options. Such information has already been partly collected in the CMP network study (AUDA-NEPAD, 2023f). Obtaining all locational information on supply options may still present a challenge for modellers, but as such information resides with countries, continued stakeholder dialogue will remain of utmost importance.

The second improvement pertains to refining the contributions to reserve margin introduced in Table 1. For instance, the reserve margin contribution of interconnectors depends on a number of concomitant factors, such as demand profiles, VRE generation penetration and profiles and available dispatchable capacity. Since the reserve margin contribution of interconnectors is a parameter to which continent-level results may exhibit sensitivity, this potential improvement could be among the priorities. In reality, different countries work with different reserve margin assumptions for their planning, so consensus on model assumptions could perhaps best be obtained through stakeholder dialogue.

The third improvement pertains to including more granular demand projections. In the current version of the SPLAT-CMP model, load profile shapes were assumed to remain invariant even under average demand growth; however, it is well documented that climate change and socio-economic development, as well as changes in the demand structure (*e.g.* due to the electrification of transport) may have ramifications for the seasonality and the daily peak of power demand, for example (Toktarova *et al.*, 2019). In the future, approaches such as the aforementioned (Toktarova *et al.*, 2019) could be integrated into demand projections for SPLAT-CMP, notwithstanding large uncertainties surrounding, for example, the impact of economic development on various demand types, to inform sensitivity analyses. AUDA-NEPAD is already planning to upgrade the demand modelling methodology under pillar 1 (see Section 1) in the next phase of the CMP, which could then feed into new runs with SPLAT-CMP.

The fourth improvement pertains to further refining the battery storage modelling, and allowing the model to either endogenously optimise the power/energy ratio, or to allow for different candidate batteries with various storage durations differentiated by CAPEX but with potentially similar contributions to the reserve margin. In practice, short-duration batteries could become essential for providing ancillary services, for example. Ancillary services such as operating reserves would also have to be coded, as done in (Welsch *et al.*, 2015).

The fifth improvement pertains to a more dynamic representation of instantaneous VRE penetration limits, which act as a proxy for a hard cap on the overall amount of VRE penetration. Firstly, the penetration limits could increase over time as power systems grow and gain in flexibility. Further, the limit could be a function of transmission system size, level of interconnection and level of dispatchable capacity (*e.g.* reservoir hydropower) in each country. Such options could be investigated well with IRENA's FlexTool, for example.

The sixth improvement pertains to a better regional and country-level differentiation of fuel prices for coal, gas and HFO/diesel. Such differentiation could take into account the differences in import costs between coastal countries and landlocked countries, as well as consider that choosing between imports and domestic resources is not an either/or choice, but could depend on numerous factors, and that various countries may exploit domestic resources in the future that have not yet been commercially tapped.

The seventh improvement pertains to experimenting with country-level differentiation of discount rates and technology-specific hurdle rates (see Section 2.3.4). It would require some thought and justification, but the uniform 10% that is currently assumed in the SPLAT-CMP model is quite far from what is currently achieved in certain projects on the continent. Country- or technology-differentiated discount rates can significantly affect the optimised capacity prospects of various renewable generation technologies. The first CMP exercise assumed the same discount rate across all countries to ensure no discrimination based on country-specific investment risks. Similarly, the same discount rate was assumed across all technologies, primarily to avoid increasing the model complexity. Nevertheless, the SPLAT-MESSAGE framework can be enhanced in future to allow distinct discount rates by country or technology. In particular, it is reasonable to assume that the discount rates can differ from technology to technology because of the prominent differences in WACC as observed in the current renewable power generation cost statistics (IRENA, 2023c).

The eighth improvement pertains to including the option of adding hydrogen as an energy carrier for either domestic use or for export purposes. An initial proposal to model parameter formulation to include green hydrogen production for export was previously introduced in the SPLAT models for North African countries (IRENA, 2023b), which could serve as a blueprint to roll it out across the SPLAT-CMP model.

The ninth improvement pertains to exploring the further decarbonisation potential offered by the demand-side management of loads encompassing: (i) traditional electric loads; (ii) electrolyser loads corresponding to hydrogen demand forecasts; and (iii) projected electrified loads of the various traditionally non-electric energy sectors such as transport, heating and cooling. These considerations are part of the focus of the forthcoming IRENA analyses that will chalk out the Renewable Energy Transition Outlooks (RETOs) up to 2050 for the five regions of Africa (Central, Eastern, Northern, Southern and Western).

6. CONCLUSION/OUTLOOK

One of the most important contributions of the SPLAT-CMP model development has been to kick off a process at the institutional level of AUDA-NEPAD and the African power pools to design a collaboration mechanism around energy modelling, using a harmonised model and approach that allows easy updating and reproduction of studies on capacity expansion planning. For CMP, being the first continental masterplan for electricity generation and cross-border transmission expansion in Africa, gathering the trust and ownership of the African Union's member countries to endorse the use of the model is of utmost importance. Therefore, the availability of a clear and complete description of the CMP model cannot be overlooked. This IRENA report contributes to this important need.

Beyond this, the CMP process aims to establish a long-term continent-wide planning process for power generation and transmission to support the planning towards an African Single Electricity Market (AfSEM). This process has been supported by IRENA and the IAEA as modelling partners. IRENA and the IAEA believe that the improvements made to the SPLAT model in this process may benefit the entire energy modelling community. This report thus also serves to share the principles applied and the lessons learnt with interested stakeholders from technical teams in, for example, African power pools, country-level utilities and the wider academic community, who could apply similar methods in other energy modelling tools, such as OSeMOSYS and PyPSA. These models could then play a role in further corroborating the findings obtained by AUDA-NEPAD using SPLAT-CMP.

DATA AVAILABILITY STATEMENT

The hydropower profiles from the AfREP-Hydro database are available open-access through HydroShare (version 2.3 on https://www.hydroshare.org/resource/197eab83ae424be3804ee154ed98aea8/).

The Python code used to generate the hydropower profiles from the AfREP-hydro database, allowing users to regenerate the profiles with potentially different assumptions, is available on GitHub (https://github.com/VUB-HYDR/2021_Sterl_etal_AHA).

The solar PV and onshore wind power MSRs and corresponding clusters, including GIS shapefiles and hourly time series, are available open-access through Zenodo (version 1.1.0 on https://zenodo.org/records/7014915).

The Python code used to generate the MSRs and clusters, allowing users to regenerate the dataset with potentially different assumptions, is available on GitHub (https://github.com/SPLATteam/Model-Supply-Regions-MSR-Toolset).

The solar CSP and offshore wind MSRs and the associated model input data were developed using the MSR toolset with a few adjustments explained in Section 2.3.2. This was done to maintain consistency in the methodological approach adopted for representing all the solar- and wind-based supply resources in the SPLAT-CMP model. These data can be obtained from the authors upon request.

Other various relevant data for future efforts on capacity expansion modelling for Africa may be found in the specific studies conducted under the auspices of AUDA-NEPAD during the CMP process, which are publicly accessible on https://cmpmwanga.nepad.org/SSS.

ACKNOWLEDGEMENTS

IRENA wish to extend their gratitude to AUDA-NEPAD and the African power pools, whose collaboration has been indispensable in setting up the SPLAT-CMP model. Thanks to their efforts, the entire energy modelling community may now benefit from new insights and modelling techniques.

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APPENDIX

The table below shows the principal input data (indicative length and terrain factor) of generic interconnectors between neighbouring African countries, as described in Section 2.4. It also shows the unit cost in USD/kW and the efficiency of the line as entered in SPLAT-CMP, as shown graphically in Figure 5.

Neighbouring country #1	Neighbouring country #2	Indicative length (km)	Terrain factor	Unit cost for SPLAT-CMP technology (USD/kW)	Efficiency (%)
Somalia	Kenya	2 050	2,0	3.839	0,92
Libya	Chad	1 580	2,0	2.541	0,93
South Sudan	CAR	1 405	2,0	2.113	0,94
Sudan	Chad	1 360	2,0	2.008	0,94
Mauritania	Algeria	1 350	2,0	1.985	0,94
Sudan	Central African Republic	1 350	2,0	1.985	0,94
Mali	Algeria	1 170	2,0	1.590	0,95
Libya	Sudan	1 080	2,0	1.407	0,95
South Sudan	Kenya	1 025	2,0	1.299	0,95
Democratic Republic of the Congo	Central African Republic	1 015	2,0	1.280	0,95
Niger	Libya	970	2,0	1.195	0,95
Niger	Algeria	950	2,0	1.158	0,95
Uganda	South Sudan	930	1,5	841	0,95
Niger	Mali	900	2,0	1.067	0,96
Niger	Chad	860	2,0	998	0,96
Mauritania	Mali	850	2,0	980	0,96
Congo	Cameroon	740	1,5	746	0,96
Liberia	Guinea	700	1,5	687	0,96
Guinea-Bissau	Guinea	680	1,5	658	0,96
Senegal	Guinea	680	1,5	658	0,96
Eritrea	Djibouti	675	1,5	651	0,96
Congo	Central African Republic	670	2,0	859	0,96

Neighbouring country #1	Neighbouring country #2	Indicative length (km)	Terrain factor	Unit cost for SPLAT-CMP technology (USD/kW)	Efficiency (%)
South Sudan	Democratic Republic of the Congo	600	2,0	929	0,96
Guinea	Côte d'Ivoire	600	1,5	697	0,96
Senegal	Mali	600	1,5	697	0,96
Cameroon	Central African Republic	575	2,0	873	0,96
Morocco	Mauritania	540	2,0	797	0,96
Tanzania	Mozambique	525	1,5	574	0,96
Rwanda	Democratic Republic of the Congo	520	1,5	566	0,96
South Sudan	Ethiopia	500	2,0	713	0,97
Mali	Guinea	500	1,5	535	0,97
Libya	Egypt	470	1,5	801	0,97
Kenya	Ethiopia	440	1,5	726	0,97
Tanzania	Democratic Republic of the Congo	435	1,5	714	0,97
Niger	Burkina Faso	420	1,5	678	0,97
Nigeria	Chad	380	1,0	391	0,97
Sierra Leone	Liberia	360	1,5	542	0,98
Chad	Central African Republic	350	2,0	695	0,98
Burkina Faso	Benin	350	1,0	219	0,98
Zambia	Angola	340	2,0	667	0,98
Niger	Benin	330	1,5	480	0,98
Uganda	Democratic Republic of the Congo	330	1,5	480	0,98
Senegal	Guinea-Bissau	320	1,5	459	0,98
Sudan	South Sudan	320	1,5	459	0,98
Tanzania	Burundi	310	1,5	440	0,98
Mali	Burkina Faso	300	1,5	420	0,98
Namibia	Angola	300	1,5	420	0,98
Zambia	Botswana	290	1,5	401	0,98
Nigeria	Benin	286	1,0	263	0,98

Neighbouring country #1	Neighbouring country #2	Indicative length (km)	Terrain factor	Unit cost for SPLAT-CMP technology (USD/kW)	Efficiency (%)
Somalia	Ethiopia	250	2,0	440	0,98
Liberia	Côte d'Ivoire	250	1,5	330	0,98
Somalia	Djibouti	240	2,0	847	0,98
Libya	Algeria	240	1,5	635	0,98
Togo	Burkina Faso	215	1,0	361	0,99
Chad	Cameroon	210	1,0	349	0,99
Gabon	Congo	210	1,0	349	0,99
Democratic Republic of the Congo	Burundi	200	1,5	489	0,99
Sudan	Eritrea	200	1,5	489	0,99
Ethiopia	Djibouti	200	1,0	326	0,99
Senegal	Mauritania	200	1,0	326	0,99
Gabon	Cameroon	195	1,5	472	0,99
Zimbabwe	Botswana	190	1,0	304	0,99
Tanzania	Kenya	190	1,0	304	0,99
Tanzania	Malawi	180	1,5	423	0,99
Zambia	Mozambique	180	1,5	423	0,99
Zimbabwe	Namibia	180	1,5	423	0,99
Senegal	Gambia	180	1,0	282	0,99
Tanzania	Rwanda	160	1,0	241	0,99
Ethiopia	Eritrea	150	1,5	332	0,99
Côte d'Ivoire	Burkina Faso	150	1,5	332	0,99
Sierra Leone	Guinea	150	1,5	332	0,99
Ghana	Burkina Faso	150	1,0	221	0,99
South Africa	Mozambique	150	1,0	221	0,99
Uganda	Rwanda	150	1,0	221	0,99
Togo	Ghana	135	1,0	193	0,99
Zambia	Malawi	135	1,0	193	0,99
Zimbabwe	Zambia	135	1,0	193	0,99
Namibia	Botswana	130	1,5	277	0,99

Neighbouring country #1	Neighbouring country #2	Indicative length (km)	Terrain factor	Unit cost for SPLAT-CMP technology (USD/kW)	Efficiency (%)
Democratic Republic of the Congo	Congo	130	1,0	184	0,99
Ghana	Côte d'Ivoire	125	1,0	176	0,99
Nigeria	Cameroon	125	1,0	176	0,99
Sudan	Egypt	120	1,5	605	0,99
Equatorial Guinea	Cameroon	120	1,0	403	0,99
Morocco	Algeria	120	1,0	403	0,99
Mozambique	Malawi	110	1,0	356	0,99
Tunisia	Libya	110	1,0	356	0,99
South Africa	Namibia	105	1,0	333	0,99
Zambia	Tanzania	100	1,0	312	0,99
Sudan	Ethiopia	90	1,0	285	0,99
Niger	Nigeria	85	2,0	544	0,99
Democratic Republic of the Congo	Angola	80	1,5	388	0,99
Zimbabwe	Mozambique	80	1,0	258	0,99
Mali	Côte d'Ivoire	75	1,5	368	0,99
Uganda	Tanzania	70	1,5	348	1,00
Zambia	Namibia	70	1,5	348	1,00
Zambia	Democratic Republic of the Congo	70	1,0	232	1,00
Tunisia	Algeria	65	1,0	219	1,00
South Africa	Botswana	60	1,0	205	1,00
Togo	Benin	60	1,0	205	1,00
Uganda	Kenya	50	1,0	179	1,00
Zimbabwe	South Africa	50	1,0	179	1,00
Gabon	Equatorial Guinea	45	1,0	165	1,00
Rwanda	Burundi	30	1,0	126	1,00
South Africa	Lesotho	20	1,0	99	1,00
Mozambique	Eswatini	15	1,0	86	1,00
South Africa	Eswatini	10	1,0	72	1,00

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