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MASTER OF SCIENCE IN ENVIRONMENTAL AND LAND PLANNING ENGINEERING

INTEGRATING HYDROLOGICAL CONSTRAINTS FOR HYDROPOWER IN ENERGY MODELS

The case study of the Zambezi River Basin in the Southern African Power Pool

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Abstract

Ensuring reliable supplies of energy and water are two important Sustainable Development Goals, particularly for Sub-Saharan African countries. The energy and water challenges are however not independent, and the interlinkages between them are increasingly recognized and studied using water-energy nexus approaches.

In this work, we propose an integrated modelling approach that embeds an improved characterization of hydropower generation as dependent on the hydrologic variability of the Zambesi River Basin (ZRB) into an energy model of the Southern African Power Pool (SAPP). Specifically, we use the Calliope modelling tool, which allows to form internally coherent scenarios of how energy is extracted, converted, transported and used, setting arbitrary spatial and temporal resolution and time series input data.

As in many state-of-the-art energy models, hydropower production is poorly described in Calliope as the model neglects water availability constraints and assumes hydropower plants produce at their nominal capacity in each timestep. Exploiting Calliope existing modeling components, we improve the hydrological description of the main reservoirs in the Zambezi River Basin as part of the overall SAPP model. Our improvements include the most relevant hydrological constraints, such as time-varying water availability and hydraulic head, evaporation losses and cascade releases. The model outcomes are then evaluated for different hydrologic scenarios. Finally, in order to validate the model, we simulate specific historical years and compare our results with observed energy data.

Our results demonstrate the value of advancing the hydropower characterization in energy models by capturing reservoir dynamics and water resource variability. These improvements will be particularly valuable to support hydropower management and planning expansion in African countries that rely mostly on this technology to satisfy their growing energy demand.

Sintesi

Garantire l'approvvigionamento di acqua ed assicurare l'accesso all'energia costituiscono due importanti obiettivi di Sviluppo Sostenibile (SDGs, Sustainable Development Goals), specialmente per la regione africana subsahariana. Tuttavia le sfide globali legate all'energia e all'acqua non sono indipendenti l'una dall'altra, al contrario le interdipendenze tra queste sono sempre piú riconosciute e studiate grazie ad un nuovo approccio integrato, chiamato "water-energy nexus".
Con questo lavoro si vuole contribuire ad un approccio modellistico integrato water-energy incorporando la descrizione idrologica del bacino del fiume Zambesi (ZRB, Zambezi River Basin) nel modello energetico dell'Africa meridionale (SAPP, Southern African Power Pool). Nello specifico, é stato utilizzato lo strumento di modellazione Calliope, che permette all'utente di creare scenari energetici su come l'energia viene estratta, convertita, trasportata e utilizzata, settando arbitrariamente la risoluzione spaziale e temporale e fornendo gli input come serie temporali.
Come nella maggior parte dei modelli energetici tradizionali, anche in Calliope la produzione idroelettrica é descritta superficialmente, ignorando i vincoli legati alla disponibilitá della risorsa acqua; di conseguenza si assume che gli impianti idroelettrici producano alla loro capacitá nominale in ogni istante di tempo. Sfruttando le componenti modellistiche esistenti di Calliope, in questa tesi é stata migliorata la descrizione dei principali serbatoi dello ZRB come parte integrante del modello complessivo della SAPP. Tali miglioramenti includono la modellazione dei serbatoi a cascata e i piú importanti vincoli idrologici, come la disponibilitá d'acqua, il salto idraulico e le perdite dovute all' evaporazione in dipendenza dal tempo. I risultati del modello saranno poi valutati considerando diversi scenari idrologici.
I nostri risultati dimostrano il valore aggiunto di una caratterizzazione avanzata degli impianti idroelettrici nei modelli energetici, poiché sono in grado di catturare la dipendenza della produzione energetica dalle dinamiche di bacino e dalla variabilitá della risorsa idrica. Il nostro approccio di modellazione

integrata potrebbe rivelarsi fondamentale nel supportare la gestione idroelettrica esistente e la pianificazione di nuovi impianti, specialmente in quei paesi africani che dipendono maggiormente dall'acqua per soddisfare la loro sempre crescente domanda energetica.

Executive summary

Introduction

The interlinkages and interdependencies of the Sustainable Development Goals are calling for integrated solutions (*United Nations*, 2015) to ensure secure supplies of energy (goal 6) and clean water (goal 7) while seeking to maintain robust economies and raise billions of people out of poverty. The energy and water challenges are not independent, and the linkages between them are increasingly recognized (*Pittock et al.*, 2015). The use and management of water resources can determine how much water is available for energy production, and these interdependencies are known as the "Water-Energy nexus" (*United Nations World Water Assessment Programme*, 2014).
Adopting a Nexus lens, we want to increase the detail of the hydropower component in energy models. The hydropower production characterization is typically a weakness of energy models because of the temporal resolution: if the simulation step is reduced to only some time slices in a year, an accurate description is not feasible intrinsically. Complex optimization models like MARKAL (*Fishbone and Abilock*, 1981) or TIMES (*Loulou and Labriet*, 2008) work simply on the basis of hydropower installed capacity; the expected yearly energy produced is provided exogenously with respect to historical data, neglecting water resource variability and reservoir dynamic.
Furthermore, an increasing penetration of renewable technologies in the energy sector highlights the interest on operating models (*Pfenninger et al.*, 2014). This leads to the need of a more accurate modelling also of hydropower production with the scope of obtaining an optimization on the operational point of view.
In this work we build an integrated water-energy model improving the description of hydropower production with hydrological constraints related to water availability and reservoirs dynamic. Our work take inspiration from what was done with the open source OSeMOSYS model in *Carlino* (2018) but employing Calliope, an energy model which better answer to the challenging of temporal and spatial resolution.

Methodology

For our work we decided to use Calliope modelling tool. Calliope is a free and open-source linear programming model very flexible in technology definition and able to deal with high spatial and temporal resolution (*Pfenninger and Pickering*, 2018); It uses the power nodes modelling framework (*Heussen et al.*, 2010), in which each location is described as a point of a network, with its own technologies and demands to be satisfied (power demand, heat demand, etc.); then the energy system is optimized by minimizing the total system cost.
In a scenario with high share of hydropower production, a description based only on the installed capacity is not exhaustive: internal dependencies between hydropower production and water resource have to be implemented. In the following sections we explain how we modelled the hydrological dynamic of a multi-cascade-reservoirs hydropower system. Additionally, we built an external loop to account for time-variable hydraulic head dependent on reservoir level and evaporation losses dependent on reservoir surface. The overall scheme of our integrated modelling strategy is illustrated in fig.1. For the description of all the others technologies, one can refer to Calliope online documentation[1].

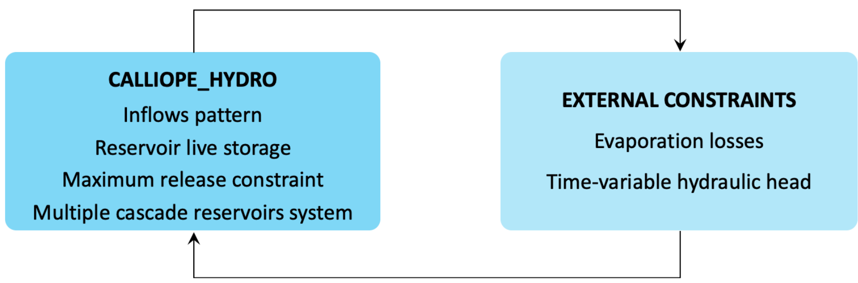

Figure 1: *Scheme of hydrological constraints implementation.*

Modelling reservoirs

In energy models, usually the system boundaries are set at the political scale. When dealing with hydropower, also basin boundaries have to be considered, accounting for hydrological connections between different hydropower plants. In order to do so, we modelled a multi cascade reservoirs system, in which the release from the upstream water storage has to be traced as additional inflow to the downstream one. Fig.2 shows a system with two cascade reservoirs; the

[1] https://calliope.readthedocs.io/en/stable/

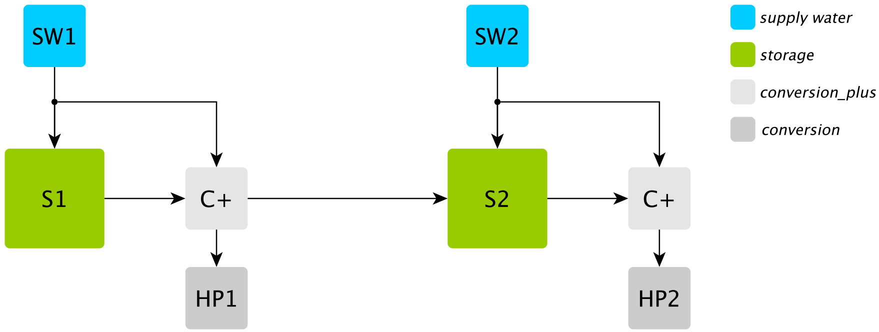

Figure 2: *Two cascade reservoirs system configuration.*

configuration could be extended to n-reservoirs.
We modelled the reservoirs (S) with a *storage* technology defining its main characteristics: storage capacity, storage level at first time step and maximum water release (i.e. the maximum flow which can be turbined). The storage capacity has been defined as the useful capacity between the maximum and the minimum storage operational value (i.e. the live storage). Calliope gives the possibility of imposing the condition of cycling storage, meaning that at the final time steps the storage level is to the initial one. To further increase the hydrological dynamic accuracy, we customized Calliope original code decoupling the initial storage state with the final one.
The *water supply* technology (SW) emulates the inflow, namely the waterflow entering the storage from precipitations and tributary rivers but not accounting for the water released by upstream reservoirs. It takes as input an external timeseries representing the hydrological resource available.
The technology that brings in input the water resource and transform it into electric energy is properly a *conversion* technology (HP), representing the typical operation of a hydropower plant. The conversion is performed through an efficiency coefficient that transforms the potential energy of water into electricity, computed as follow:

$$\eta = \rho * g * head * \eta_{turbine} * \frac{1}{3600} \quad (1)$$

with $\rho = 1000\,kg/m^3$ water density, $g = 9.8\,m/s^2$ acceleration of gravity, $head =$ geodetic hydraulic head $[m]$ available at the plant, $\eta_{turbine} =$ turbine efficiency, and finally $1/3600$ is the conversion coefficient necessary to express the electric energy in kWh.
The presence of a *conversion_plus* technology (named "C+") is crucial to connect the two water systems, because when the *conversion* technology (HP) converts

the inlet resource (i.e. water) into a new carrier (i.e. electric energy), the resource in input is not available anymore. The *conversion_plus* technology (C+) supports several carriers as output, being able to "duplicate" the water release, making one stream go into the hydropower plant (HP) to produce electricity and making the twin-stream flow into the cascade reservoir.
This modelling structure gives also the possibility of connecting two reservoirs in different locations or, in case of transboundary reservoirs, modelling multiple hydroelectric power plants in different nodes. To fully implement such systems, a *transmission* technology is required. In Calliope, the *transmissions* allow to exchange the same carrier between different nodes.

Modelling spillage

The spillway of a dam is a gateway from which the water is released skipping the turbines; thus the spillage occurs when the water level reaches the maximum operational level of the dam. The latest updated version of Calliope does not provide a modelling component which is able to be activated when given conditions occur, e.g. when the storage reaches its maximum capacity. For this reason, we decided to model the spillage as a *conversion* technology connecting two cascade reservoirs but with a conversion efficiency equal to zero. We made this choice in order to discourage the arbitrarily allocation of water from upstream to downstream reservoir according to an economical optimization. Setting the efficiency equal to zero, the spillage is modelled as a wasted water flow in order to be minimized by Calliope optimization. The modelling scheme proposed ensures a solution for each scenario, but the water spilled never reaches the downstream reservoir, for this reason the activation of spillage introduces an error in the model solution, which has to be carefully evaluated to understand how much it affects results.

External loop implementation

In this section we explain how we completed the hydrological dynamic implementing storage losses due to evaporation and defining the time-varying hydraulic head, both dependant on the storage. There is no technology in Calliope able to define such dependencies between variables at each time step of the simulation, neither it would be possible to further develop such a feature because problem linearity would be compromised. To implement this constraints, we exploit an external loop which interacts with Calliope storage timeseries, inspired by the work of *Del Pero et al.* (2019).

Evaporation losses

The evaporation of water stored in a dam could be an important source of losses for very extended reservoirs in tropical climate zones. Calliope provides a predefined constraint which allows to define a storage loss as a fraction of total capacity per hour (also in the form of timeseries). In this way we can evaluate storage losses due to evaporation at each timesteps and provide it to Calliope as an exogenous timeseries.

Once evaporation losses are evaluated as a function of reservoir surface thanks to the net evaporation coefficient (2), the storage loss timeseries are computed as in 3:

$$evap\_loss_t \left[\frac{m^3}{h}\right] = evap\_coeff_t \left[\frac{m}{h}\right] * surface_t\,[m^2] \tag{2}$$

$$storage\_loss_t = \frac{evap\_loss_t\,[m^3/h]}{storage\_capacity\,[m^3]} \tag{3}$$

where $evap\_coeff_t$ is a time-varying parameter accounting for seasonal variation of the net evaporation. The $surface_t$ is dependent on the storage and can be computed once hydrological data about the reservoir *storage-surface curve* are known. Here an issue arises: the storage timeseries is one of the outputs of Calliope optimization; it can be extracted only at the end of simulation. Consequently, storage losses which are implemented in a new iteration are computed on the basis of storage timeseries of the previous optimization. This is the reason why an external loop is required.

The hydraulic head

When the storage level variation is of the same order of magnitude of the overall hydraulic head it may influence the hydroelectric conversion efficiency, which can be provided in Calliope as an input timeseries instead of a single parameter.

The hydraulic head is function of the reservoir level, thus of the storage. Similarly to evaporation losses, it can be easily evaluated once hydrological data about reservoir *storage-level curve* are known. It is soon clear that, in order to compute the conversion efficiency timeseries dependent on time-varying hydraulic head, we need the same external iterative process adopted to evaluate storage losses. The complete external loop implementation is illustrated in fig.3.

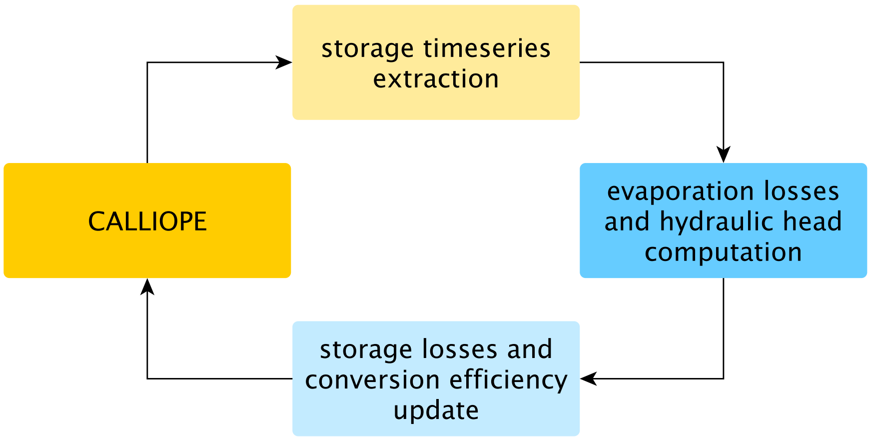

Figure 3: *External loop implementation.*

Case study

Our modelling framework was applied in order to improve the hydrological description of the main reservoirs of the Zambezi River Basin (ZRB) as part of the overall Southern African Power Pool (SAPP).
In the SAPP, hydropower will play a key role in the future power generation mix as well as at present. Individually many SAPP members are already strongly dependent on hydropower production: Zambia and Mozambique rely on hydro for 80% of their electricity generation also exporting their hydroelectric energy, while Zimbabwe hydropower production accounts for up to 60% of the total [2].
As deeply described by *The World Bank* (2010) and *Beilfuss* (2012), the Zambezi River Basin has one of the most variable climates of any major river basin in the world making the entire ZRB higly susceptible to extreme droughts and floods, with considerable impact on hydropower production (fig.4). In such complex environmental system a new approach where hydropower is planned basin-wide considering the whole energy system where the basin is included may lead to interesting results.
Calliope exploits the power nodes modelling framework, so each node of our network is an entire country. Thanks to more detailed data available, Mozambique was modelled with two nodes, one for the South and one for the North-Center of the country (fig.5). On the other hand, some countries are not modelled. Angola, Tanzania and Malawi are not connected to the grid and are not part of the Zambezi River Basin; Lesotho and Swaziland are excluded from our network because of their negligible contribution to the energy generation,

[2](data source: `https://www.iea.org`)

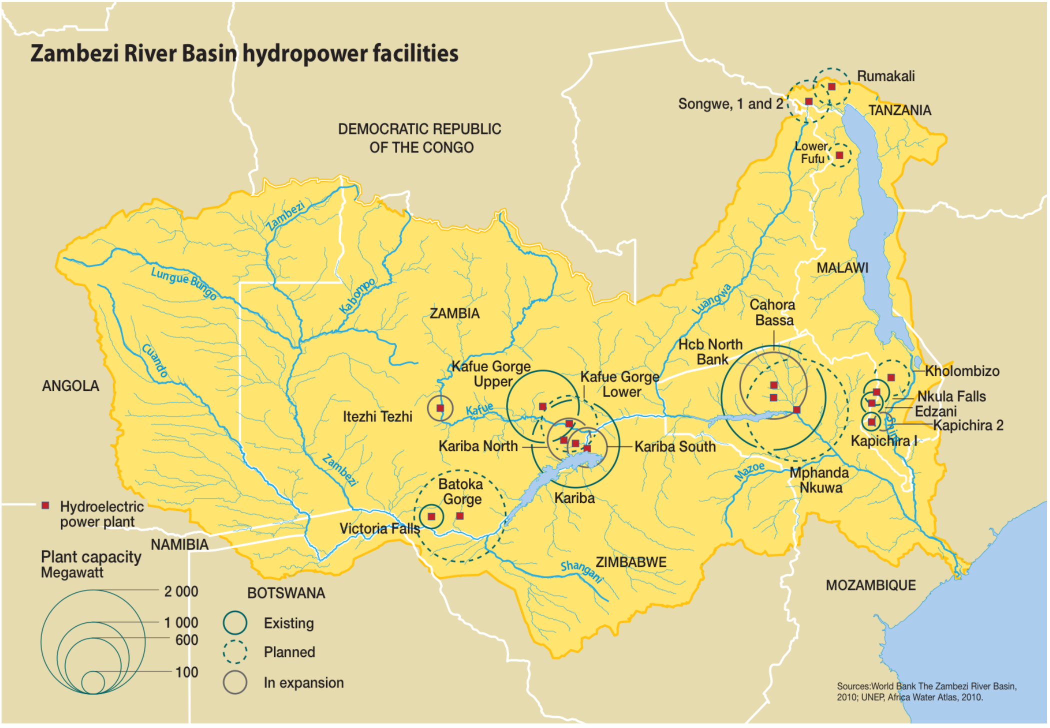

Figure 4: *The Zambezi River Basin and its hydropower plants.*

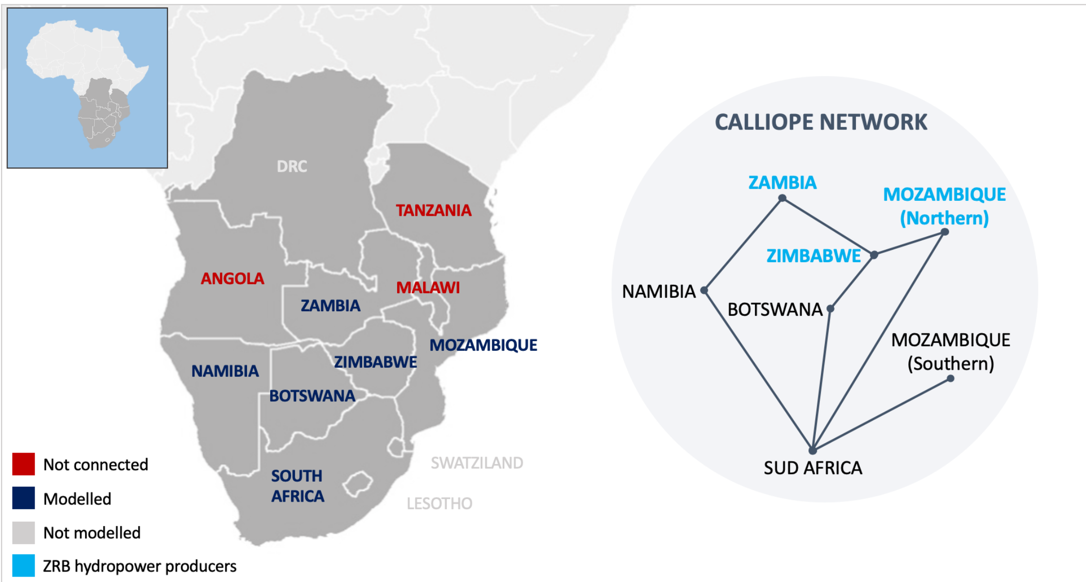

Figure 5: *SAPP countries and modelling network.*

equal to the 0.32% of SAPP total capacity (*SAPP*, 2018). The Democratic Republic of Congo is also not modelled; the main reason is its high hydropower installed capacity which we would have described in a traditional way because of lack of hydrological data, deeply limiting the effectiveness of our work. Anyway, DRC covers its total energy demand relying mostly on domestic power production, with import and export having the same order of magnitude of the statistical error[3]. Thus we can assert that DRC is almost operating like a not connected country.

Modelling ZRB

We implemented our advance modelling scheme for the four main dams of the Zambesi River Basin: Itezhi-Tezhi ("ITT", 120 MW), Kafue Gorge ("KGU", 990 MW), Kariba ("KA", 1.8 GW) and Cahora Bassa ("CB", 2 GW). The ZRB hydropower plants modelling configuration is represented in fig.6.

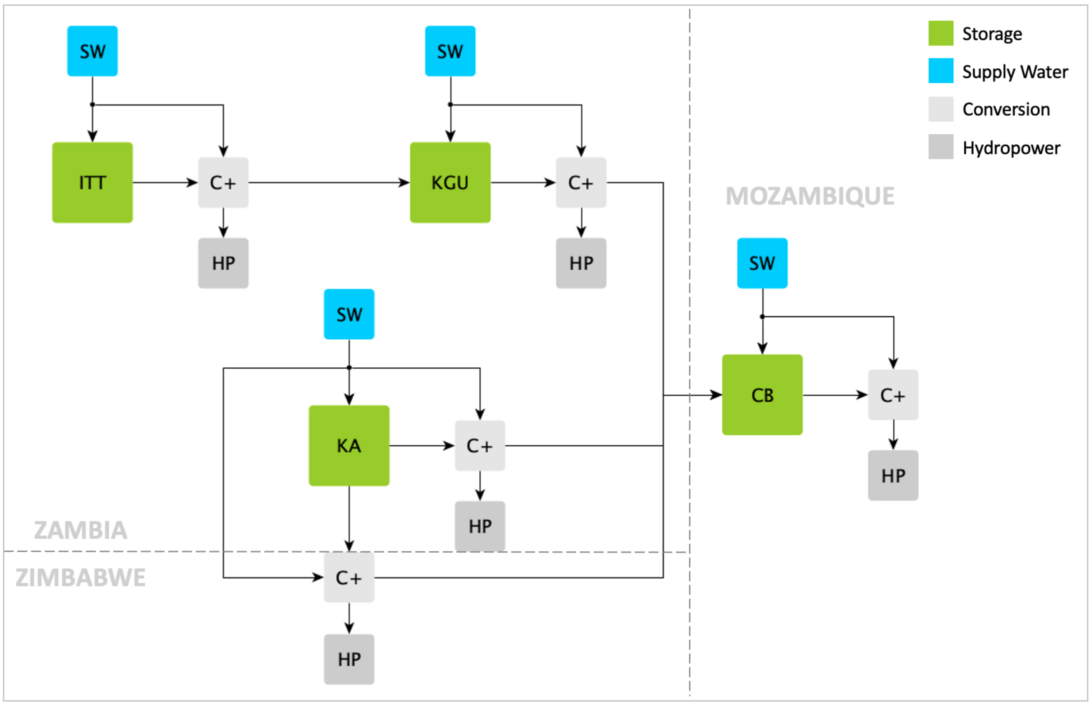

Figure 6: *ZRB configuration scheme in Calliope.*

Inflow timeseries in input come from the ADAPT project (*Matos et al.*, 2015). Regarding storage technology parameters, data about reservoirs operational constraints as maximum and minimum release come from *Gandolfi et al.* (1997), the Zambezi River Authority[4] and Hidroeléctrica de Cahora Bassa[5]. Storage initial and final values are extracted from dams operational rule curves (*Cervigni et al.*, 2015). In order to compute evaporation losses and variable hydraulic head, evaporation rates are provided by *Beilfuss and dos Santos* (2001) while

[3]Data source: https://www.iea.org/data-and-statistics/data-tables?country=CONGOREP&energy=Electricity&year=2017

[4]http://www.zambezira.org

[5]https://www.hcb.co.mz

reservoirs level-storage and surface-storage curves come from *The World Bank* (2010).

Simulation settings

Our analysis is splitted into two phases: the first one aims at simulating the system under different hydrological scenarios, in the second one we validate our model with respect to observed data.
The simulation time-step follows the hourly power demand profile. The time horizon should be set in order to capture the full hydrological dynamic of reservoirs under analysis (i.e. 5 years), but due to the high computational effort we limited the time horizon to 2 years. Then we explored hydrological variability thanks to different inflow scenarios simulating the so-called "Monte Carlo analysis". We exploited twenty years of historical inflow data (from 1986 to 2005) in order to run 10 different experiments. Fig.7 shows cumulated inflow variability for each historical year and for each reservoir.

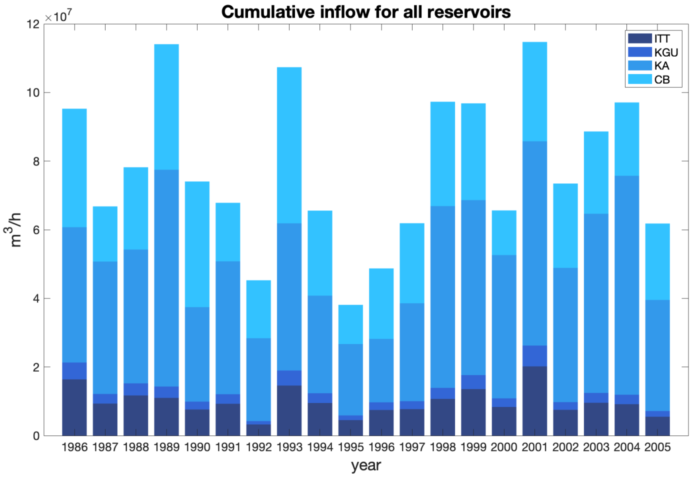

Figure 7: *Cumulated hystorical inflow from 1986 to 2005 for Zambesi River Basin reservoirs.*

Simulations start the first day of January and end the last day of December, thus the initial storage capacity is set referring to dams operational rule curve values in January; then the cycling storage option is imposed, meaning that the final value is equal to the initial one. Reservoirs main parameters are summarized in table 1, in which the initial storage values are expressed as a percentage of the live storage capacity.
As explained above, an iterative external loop is used in our model to evaluate evaporation losses and time varying hydraulic heads. For each simulation, 20 iterations are run and the convergence of the procedure is verified as discussed

Table 1: *ZRB reservoirs Calliope_hydro main parameters*

Parameters	Itezhi-Tezhi	Kafue Gorge	Kariba	Cahora
Live storage [m^3]	$5.18*10^9$	$1.18*10^9$	$6.47*10^{10}$	$5.17*10^{10}$
Hydropower capacity [MW]	120	990	1080	2075
Maximim turbines release [m^3/h]	612	252	2040	2260
Maximim hydraulic head [m]	40.5	397	110	128
Maximum storage level variation [m]	25	5	11	35
Initial storage [%]	0.6049	0.3257	0.7715	0.854

in the next section.
Simulations are performed without setting any constraint on technologies production, letting the model minimize the overall system cost; for this reason we do not expect results to mirror the actual SAPP production because they will represent the optimal grid operation. This motivated a further modification of the model with the goal of better reproducing the observed operation of the system in a specific year. For this reason, we imposed a rate of minimum production for coal based technologies and set also historical initial and final storage values of ZRB reservoirs.
The analysis of the results will be discussed comparing the advanced hydropower modelling (*Calliope_hydro*) with the equivalent standard version (*Calliope_base*), where hydropower is modelled only providing installed capacity. Simulations settings for each experiment are summarized in tab.2.

Table 2: *Simulations settings for all the experiments considered.*

Settings	*Calliope_base* simulation	*Calliope_hydro* simulations										
	s0	**s1**	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**	**s8**	**s9**	**s10**	**sC1**
Time horizon (years)	2	2	2	2	2	2	2	2	2	2	2	1
Advanced hydropower modelling	✘	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Inflow pattern	✘	1986-87	1988-89	1990-91	1992-93	1994-95	1996-97	1998-99	2000-01	2002-03	2004-05	1998
Additional constraints	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	coal capacity factor

Results

Results analysis can be splitted into two phases. In the first one, we evaluate *Calliope_hydro* outcomes variability related to different hydrological scenarios. In the second phase, we discuss results obtained adopting models configurations which improve *Calliope_hydro* in order to respect the realistic operation of coal-based plants. This will be done from a comparative point of view with observed energy data validating *Calliope_hydro* results.

Calliope_hydro hydrological variability

In order to test the improved version of *Calliope_base* (i.e. *Calliope_hydro*), we simulated 10 different hydrological scenarios derived from the historical time-series of inflow of the main reservoirs in the Zambezi River Basin. In particular, we first refer to a single simulation performed over the 1996-1997 inflow scenario and focus on the hydropower production in the ZRB. In this period inflows are not particularly abundant and spillage technology is never activated by the model.
In fig.8, 9 and 10 the domestic power production of respectively Zambia (ZA), Zimbabwe (ZW) and Mozambique North-Center (MZn) is reported, for *Calliope_base* (on the left) and *Calliope_hydro* (on the right). *Calliope_hydro* results show the different contribution of the ZRB hydropower plants: Itezhi-Tezhi (ITT), Kafue Gorge Upper (KGU), Kariba (KA) and Cahora Bassa (CB). *Calliope_hydro* allocates hydropower production according to water availability, while *Calliope_base* lets hydropower produce at its nominal capacity every time of the year. This simplistic strategy yields to an unrealistic dispatchability of energy production, risking to overestimate hydropower generation especially in dry periods. This limitation of *Calliope_base* is particularly highlighted by the results obtained for Zambia and Zimbabwe power productions, where hydropower is largely overestimated. In Zambia it exceeds power demand and the 29% of total production is exported to Zimbabwe, which similarly satisfies most of its energy requirements thanks to hydropower production. Hydroelectric in Zimbabwe covers 82% of its demand in *Calliope_base* while in *Calliope_hydro* it is reduced to 27%. In *Calliope_base*, Zimbabwe is importing energy from Zambia to partially cover its internal demand and partially export it to Botswana; this happens because there is not a direct transmission line connecting Zambia and Botswana. Instead in *Calliope_hydro* Zambia is not exporting and needs to cover its energy demand with 11% of coal-based generation. As a consequence, Zimbabwe needs to import energy from Mozambique North,

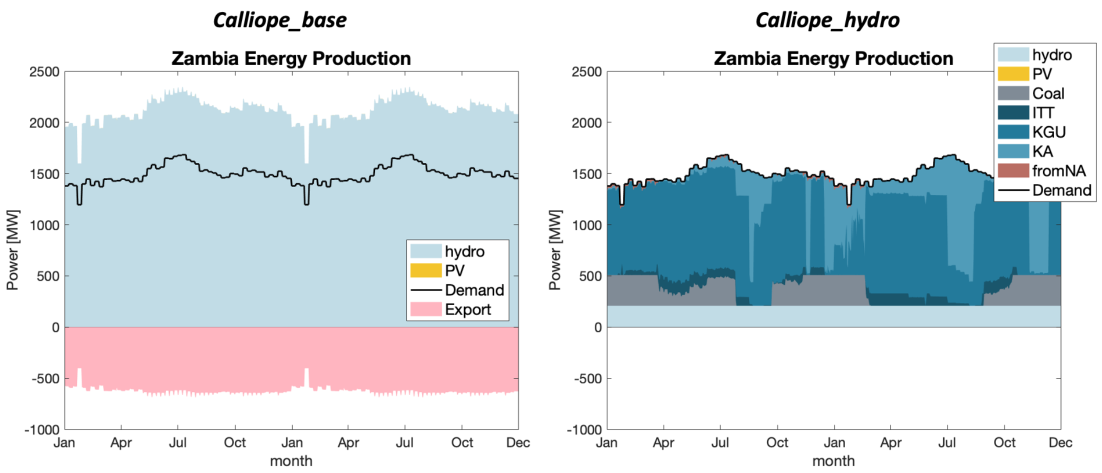

Figure 8: *Zambia energy production comparison between Calliope_base and Calliope_hydro*

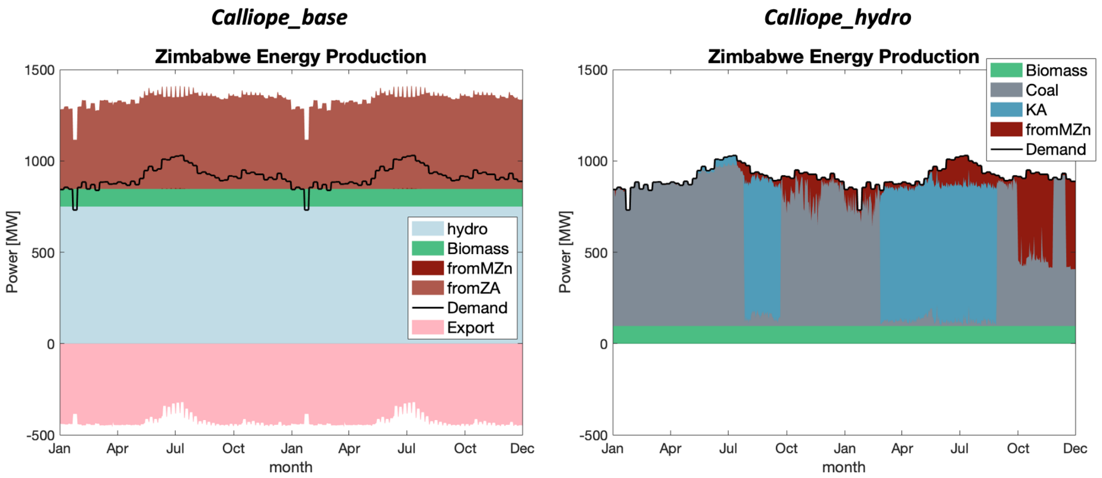

Figure 9: *Zimbabwe energy production comparison between Calliope_base and Calliope_hydro*

namely from Cahora Bassa hydropower plant, suspending export.
Concerning Cahora Bassa in Mozambique, it usually produces at its nominal capacity thanks to its configuration and location. It is the last reservoir of the cascade configuration; in addition to its inflow, it takes as input all the releases of upstream reservoirs. That's why it is less influenced by dry season and its hydropower installed capacity is the highest of the ZRB plants. Differences between models can be appreciate in terms of suspendend hydropower overproduction as export to South Africa.

In order to investigate how the model cope with diverse hydrological conditions, we analyse *Calliope_hydro* behavior under all the other scenarios explorable, including very wet and very dry periods. In particular, we compare our reference scenario (1996-1997), which is one of the driest, with the inflow

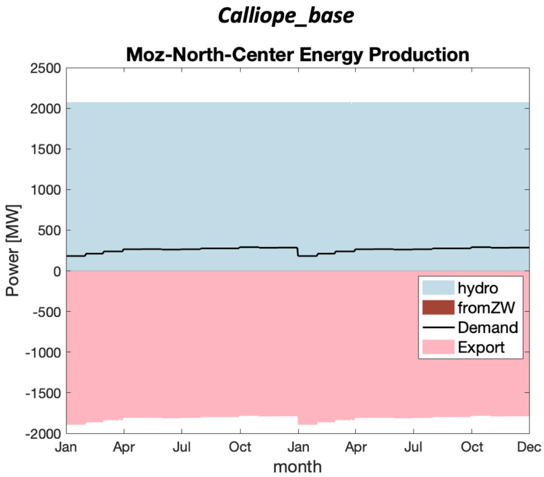

Figure 10: *Mozambique North-Center energy production comparison between Calliope_base and Calliope_hydro*

observations over the period of 1988-1989, which is one of the wettest. Focusing on the results obtained for Zimbabwe (fig.11), we can notice the large differences in power generation comparing a dry and a wet scenario. In wet years, the energy system regulation changes and hydropower production become the main source of electricity covering almost all the demand. While energy generation from coal in the reference scenario cover more than half of the total production, it almost disappears in the wet scenario.

Analogue considerations can be done for the case of Zambia (fig.12). In wet years, generation from coal is completely replaced by 100% hydropower energy production. Water resource availability and associated hydropower potential exceeds Zambia power needs, enabling export to Zimbabwe, which in

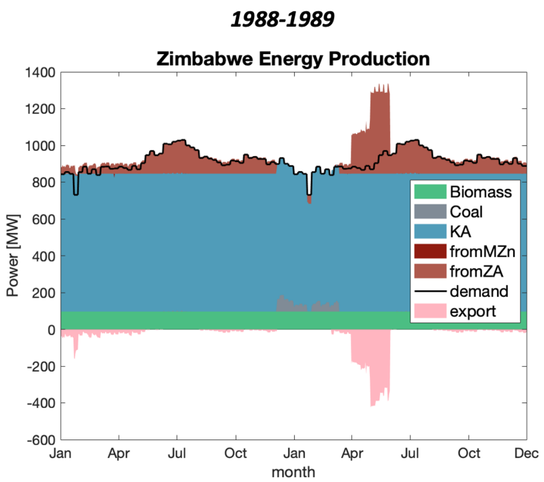

Figure 11: *Zimbabwe energy production comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

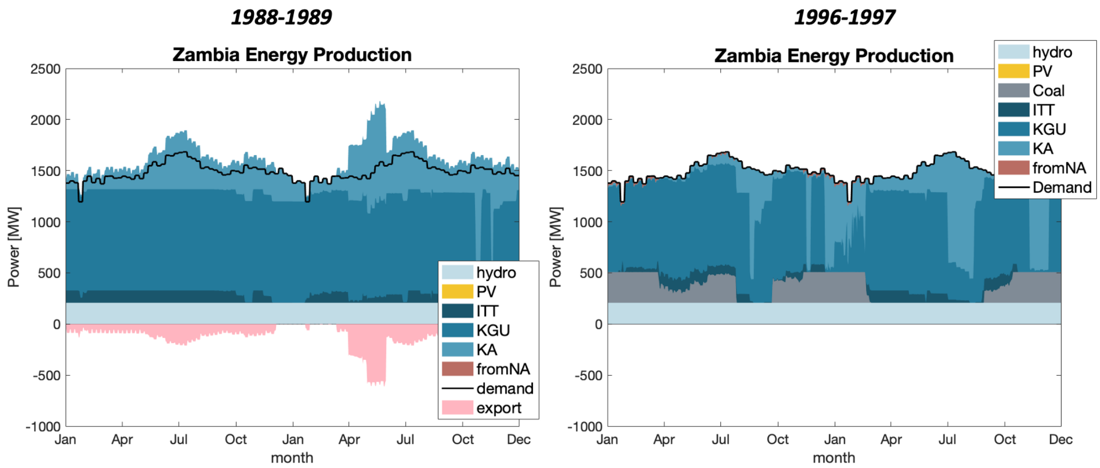

Figure 12: *Zambia energy production comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

turn exports to Botswana (as also observed in the previous section). This highlights how water availability influences also countries in which the advanced modelling of hydropower is not present.
Results obtained for all the 10 hydrological scenarios are summarized in tables 3 and 4, where the variation of the production mix for respectively Zimbabwe and Zambia can be appreciated .

Table 3: *Zimbabwe power production among all hydrological scenarios.*

Technology	Zimbabwe energy mix among scenarios s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Biomass	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
Coal	17.3%	0.7%	36.6%	36.7%	69.0%	53.0%	0.01%	0.01%	14.0%	28.9%
KA	68.7%	81.6%	49.7%	48.9%	16.0%	27.2%	82.1%	82.0%	73.2%	57.2%
Import from MZn	3.0%	0.0%	3.1%	3.4%	4.2%	9.3%	0.001%	0.04%	2.2%	0.8%
Import from ZA	0.5%	7.1%	0%	0.4%	0.3%	0%	7.3%	7.3%	0%	2.53%
DEMAND [MWh]	666667	666667	666667	666667	666667	666667	666667	666667	666667	666667
PRODUCTION [MWh]	643835	619178	646123	641038	637088	604986	618011	617496	651703	644477
IMPORT [MWh]	22850	72496	20544	27440	29579	61680	94838	75757	14963	57949
EXPORT	0.003%	3.6%	0%	0.3%	0%	0%	6.5%	3.8%	0%	5.1%

Simulating observed system behavior

Up to now, we analyzed the results of *Calliope_hydro* optimization under different hydrological scenarios, without imposing any exogenous constraints about minimum power production from a specific technology. We let the model op-

Table 4: *Zambia power production among all hydrological scenarios.*

Technology	Zambia energy mix among scenarios									
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
hydro	13.9%	12.8%	13.9%	13.9%	13.9%	13.9%	12.5%	12.7%	13.9%	13.2%
PV	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Coal	0.7%	0%	5.1%	6.7%	12.1%	11.2%	0%	0%	0.9%	4.0%
ITT	6.0%	5.1%	4.3%	4.0%	3.7%	3.9%	5.3%	5.2%	4.3%	3.7%
KGU	64.8%	60.1%	58.7%	57.0%	43.7%	52.9%	59.5%	61.0%	59.6%	46.9%
KA	14.7%	22.0%	17.8%	18.5%	26.0%	17.4%	22.8%	21.2%	21.3%	32.2%
Import from NA	0%	0%	0.2%	0.01%	0.6%	0.7%	0%	0%	0%	0%
DEMAND [MWh]	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008
PRODUCTION [MWh]	1093447	1181945	1088193	1089920	1083908	1082633	1212353	1185093	1090152	1144329
IMPORT [MWh]	339	5	2116	4819	8103	7604	0	5	360	2620
EXPORT	0.35%	7.8%	0.03%	0.4%	0.2%	0.02%	10.1%	8.0%	0.05%	5.0%

timize the energy system by minimizing the total system costs. We observed that the variable generation of hydropower leads to an unrealistic usage of fossil fuel technologies, especially coal. For this reason, in this section we improve *Calliope_hydro* adopting models configurations which respect the realistic operation of coal-based plants and we validate our results comparing them to observed energy data. We select a specific year for simulation, we impose a minimum energy production for coal power plants and we model only existing technologies at that time (values were chosen looking at real energy data from the IEA [6]). In addition, we impose historical initial and final storage capacity of ZRB reservoirs allowing the model to produce an increase/decrease of storage over the 12 months of simulation.

Among the years of data available, we simulate the system behavior of 1998. Results obtained are very interesting for the case of Zimbabwe; in fig.13 we can notice how *Calliope_base* is still overestimating hydropower up to the 59% of the total production, while *Calliope_hydro* hydroelectric share is almost equal to the real 29% from IEA. 1998 was a quite wet year, thus we can expect a high hydropower production. Actually, the regulator of Kariba decided to fill the reservoir along the year, thus reducing the water available for hydropower production. This strategy cannot be modelled by *Calliope_base*. In *Calliope_base*, the impressive amount of power production exceeding the demand is exported to cover Botswana energy requirements. This happens in lower measure for the simulation performed by *Calliope_hydro*, showing how water availability affects

[6]https://www.iea.org/data-and-statistics?country=ZIMBABWE&fuel=Energy%20supply&indicator=Electricity%20generation%20by%20source

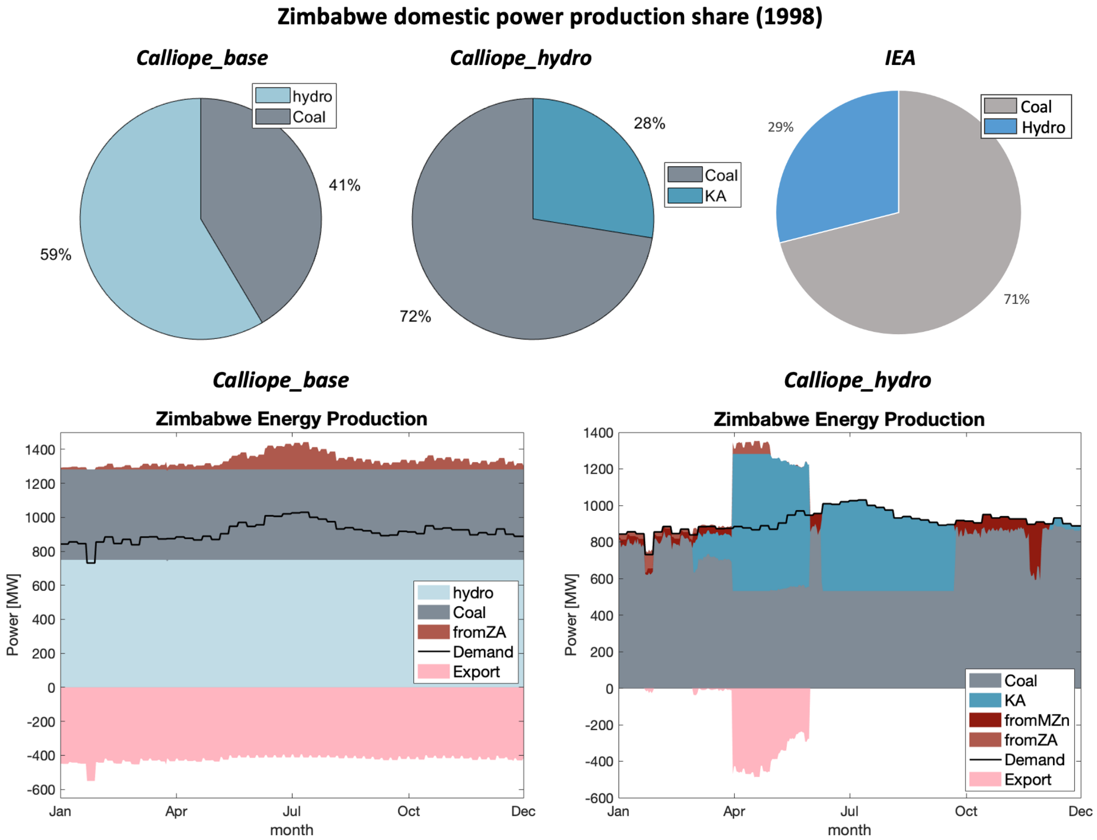

Figure 13: *Zimbabwe power production comparison (1998).*

not only ZRB hydropower producers but also the importing countries.

The spillage

We remind that the spillage is defined as a *conversion* technology linking two cascade reservoirs with null efficiency in order to discourage its activation. This means that water allocated to this technology does not reach the downstream reservoir and "leaves" the system. Given this limitation of our model, in this section we aim at quantifying the impacts of this imperfect implementation of the spillway.

Model outputs for Kafue Gorge confirmed that the small capacity of this reservoir make its hydropower plant the most sensitive to the spillway activation. Thanks to the bigger storage capacity, Ithezi-thezi reservoir is able to better manage inflow peaks and water excess, ultimately reducing the amount of water assigned to spillways. This suggests that the bigger the storage capacity, the lower and less frequent is the spillage. This is confirmed by results obtained for Kariba reservoir.

Given this clear limitations, the first check we performed verified that when the spillway is active, the reservoirs are also producing at maximum capacity by saturating the turbines; it means that the water flow assigned to the spillage technology is effectively exceeding the maximum capacity of release and missing water flow influences reservoirs water mass balance but not hydropower production. Then we quantified the error associated with this phenomenum: results show that the total amount of water spilled is in the range of 0.2% and 6.8% of the total resource ideally available at Cahora Bassa reservoir, with an average error of 2.3% across all scenarios.

Exernal loop convergence

Calliope_hydro models evaporation losses and time varying hydraulic heads by means of an external loop. The external loop should be iterated until convergence is reached, but given the high time-demanding simulations[7], we fixed the maximum number of iterations equal to 20. The convergence is then evaluated at the end of simulation as the difference between storage timeseries of the last two iterations.
Storage trajectories results suggest that in wet periods the model has less freedom of allocating water resource; high cumulated inflow or seasonal peaks represent a strong constraint for water storage management, forcing the model to an almost univocal behavior. Contrariwise, under dry scenarios the lower availability of water relax storage management constraints, letting the model more freedom for water resource allocation; thus convergence is not achieved.
Now it is essential to understand if the convergence issue is undermining the energy system optimization. Results in fig.14 illustrate Zambia energy production timeseries and share over a particularly dry simulation horizon (1996-1997) for iterations #19 and #20. We can notice that energy production share is always constant; what is slightly changing is the different allocation of hydropower production over time. Anyway, the trend of hydroelectric generation is almost preserved, with similar periods of suspended production. Furthermore, even if performing 30 iterations, results show that the optimal energy mix is reached after the first iteration, while the temporal allocation of hydropower production continue to oscillate. We can assert that *Calliope_hydro* is slightly sensitive to external loop constraints and under dry scenarios it does not reach an univocal optimal operation solution.
Thus, we conclude that the computational effort can be limited without affecting results accuracy: from an energy point of view, missing convergence does not influence the system optimization but the resource allocation over time.

[7] Running 20 iterations requires a simulation time of about 20 hours with user's interaction (simulation time estimated referring to Intel Core i7 processor, RAM 8 GB).

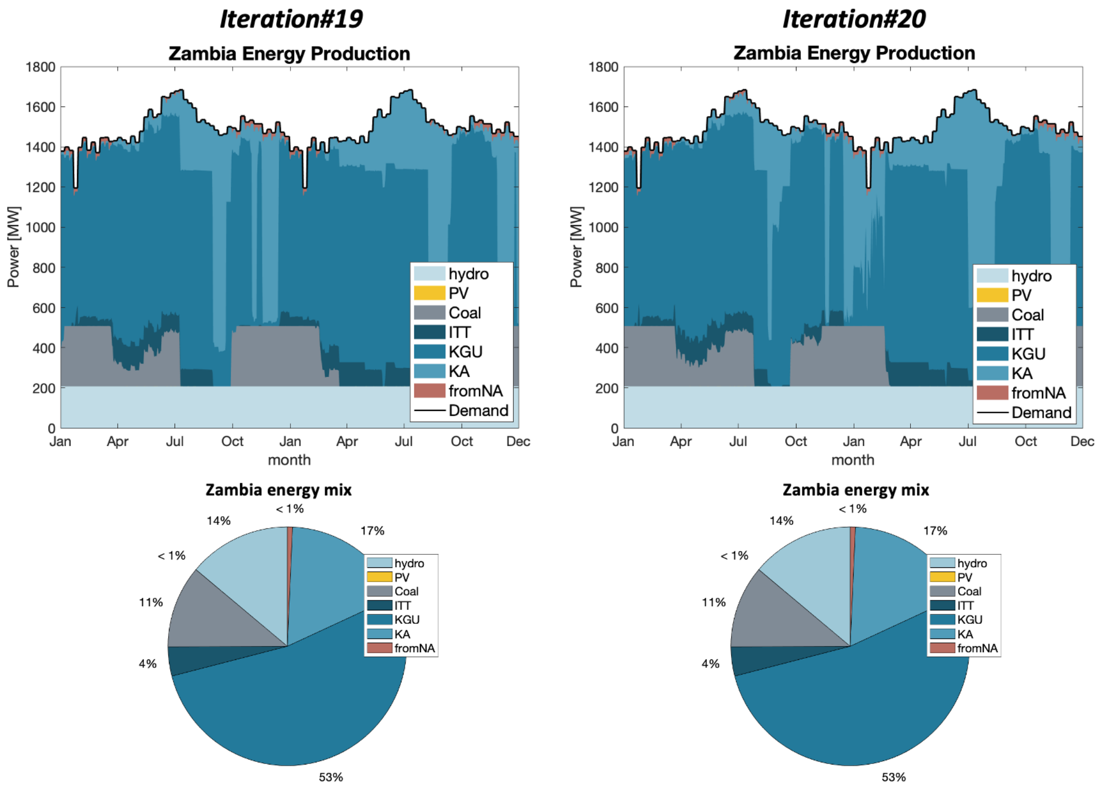

Figure 14: *Calliope_hydro power production in Zambia: comparison of the two last iterations of hydrological scenario 1996-1997.*

Conclusion

Despite weaknesses, *Calliope_hydro* is a very first water-energy model which optimizes the energy system while respecting reservoirs hydrological constraints for hydropower production. We can assert that reservoirs modelling integration ensures an improved management of hydropower and of the whole energy system, giving a better perception of how it is working considering water resource availability. *Calliope_hydro* results among all hydrological scenarios gave us the idea of how the energy mix of some african countries deeply depends on water availability enabling the possibility of exploring power pool response to dry or wet periods. Compared to *Calliope_base*, *Calliope_hydro* confirmed to be a more reliable model reproducing more realistic results which approximate IEA observed data.

Further improvements can be done in this direction in order to achieve a flawless fully integrated water-energy model. For instance, developing Calliope code, introducing new features or completely new technologies (e.g. the spillage) or refining the external loop stability. In this way a more accurate and fully exhaustive integrated description could be finally reached.

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1 Introduction

"The interlinkages and integrated nature of the Sustainable Development Goals are of crucial importance in ensuring that the purpose of the new Agenda is realized. If we realize our ambitions across the full extent of the Agenda, the lives of all will be profoundly improved and our world will be transformed for the better."

(*United Nations*, 2015)

1.1 Water and Energy: a multi-disciplinar approach

The Sustainable Development framework sets out a wide range of economic, social and environmental objectives reflecting several cross-cutting elements across the new Goals and targets. The interlinkages and interdependencies of the Sustainable Development Goals are of crucial importance in realizing the purpose of the Agenda 2030, calling for integrated solutions (*United Nations*, 2015). Within this background, ensuring secure supplies of energy and water are among the great challenges that society faces while seeking to maintain robust economies and raise billions of people out of poverty. The energy and water challenges are not independent, and the linkages between them are increasingly recognized (*Pittock et al.*, 2015).
Because nearly all hydropower is generated from dams on rivers, it provides a very specific example of how water and energy interact (*Pittock et al.*, 2015). Hydropower is the largest renewable source of electricity generation worldwide, where water itself acts as the "fuel" for generation. The amount of water consumed is determined by climate, physical characteristics of the reservoir, and

allocations to other uses, which are site-specific and variable. The use and management of water resources can determine how much water is available for energy production, and these interlinkages and interdependencies are known as the "Water-Energy nexus" (*United Nations World Water Assessment Programme*, 2014). Since water is a limited resource, hydropower production is often competing with other water-related sectors and the key to improve hydropower sustainability is an integrated approach for water and energy supply planning and management (*United Nations World Water Assessment Programme*, 2014).
Yet, hydropower production characterization is typically a weakness of many state-of-the-art energy models. With few exceptions, previous investigations fall short in assessing the holistic influence of hydrometeorological variability on bulk power systems (*Su et al.*, 2020). Indeed, hydropower is modelled under the assumption of hydrological stationarity, neglecting water resource variability and uncertainty at the core of hydrological models. On the other hand, in many state-of-the-art hydrological models (e.g. *Castelletti et al.* (2008), *Turner et al.* (2017)) the energy system is not considered in its wholeness and hydropower production is usually maximized without accounting for energy grid constraints. In addition, a mismatch occurs between traditional water and energy models in terms of spatial and temporal resolutions.
Adopting a Nexus lens, hydropower description in energy models should be improved by integrating hydrological constraints related to water availability and reservoirs dynamic. In this way the intrinsic integrated system description advocated by the water-energy nexus approach would be achieved.

1.2 Aim of the thesis

Most of the weaknesses in large scale energy systems can be exacerbated by changes in water availability, variability and predictability. Managing these interdependencies has become the focus for a wide range of new integrated policies, technologies and practicies (*IEA*, 2016). The modeling scales, resolutions, and ensemble sizes required in exploring the effects of hydrometeorological variability on energy systems present a challenge, and few (if any) models capable of performing this type of analysis are publically available (*Su et al.*, 2020).
The aim of this thesis is improving hydrological description of hydropower in energy models adopting a fully integrated approach. We will use the free and open-source optimization linear programming model Calliope because it allows a very flexible technology definition with high spatial and temporal resolution. Our approach will be tested in the case study of the Zambezi River

Basin as part of the overall Southern African Power Pool (SAPP). In this region, nearly 40 GW of hydropower could be potentially deployed in the short to medium term in order to meet growing energy demands (*Ouedraogo*, 2017). Hydropower is expected to play a key role in the future power generation mix as well as at present. Individually many SAPP members are already strongly dependent on hydropower plants of the Zambezi River Basin, both for domestic production and for export.

With our modeling strategy, hydropower production will be connected to water resource availability and variability while satisfying power demand and energy grid constraints. In particular, our contributions will focus on developing the following features of the hydropower technology:

1. We will model a multiple cascade reservoirs system including inflow patterns, maximum and minimum storage limit and maximum release constraint as a part of the overall energy system;

2. Non-linear hydrological constraints will be included thanks to external computation of evaporation losses and time-variable hydraulic head;

3. The model will be run under different hydrological scenarios in order to evaluate model outputs variation by varying inputs.

The outcomes of the improved model formulation will be compared with the original energy model adopting a traditional description of hydropower generation. Results will show the importance of capturing hydropower variability in terms of the impacts it generates on energy production and allocation over time, reflecting a more realistic operation of hydropower plants. Indeed such an integrated approach is crucial in order to optimize the water-energy systems planning and management. Finally, model potentialities and weaknesses will be discussed in order to define possible further developments of this work.

1.3 Thesis structure

Chapter 2 presents a review of the state-of-the-art methods employed in literature for implementing both separate and aggregated energy and hydrological models. Chapter 3 discusses the methodological procedure followed for full-integrating the energy model Calliope with hydrological dynamics and constraints. The resulting aggregated model will be tested on the case study of the Zambezi River Basin as part of the overall Southern African Power Pool, in an water-energy system boundaries described in chapter 4. Numerical results obtained from such an analysis will be reported in chapter 5, where each step described in the methodology is documented and commented. In the end, chapter 6 will summarize the advantages and the potential of our water-energy model, together with its limitations and possible further developments.

2

State of the Art

2.1 Energy models

Energy is central to improved social and economic well-being, and is indispensable to most industrial and commercial wealth generation (*Brew-Hammond and Kemausuor*, 2009). In a period of strong changes and challenges related to a sustainable development, an accurate analysis of the energy systems is crucial to better understand this linkages. The complexity of this analysis leads to the search for the best description of the energy sector. Many approaches have been tried we can distinguish them in two macro-category: bottom-up and top-down models.
Bottom-up features a large number of discrete energy technologies to capture substitution of energy carriers on the primary and final energy level, process substitution, or efficiency improvements. Such models often neglect the macroeconomic impact of energy policies. Bottom-up energy system models are typically cast to compute the least-cost combination of energy system activities to meet a given demand (*Böhringer and Rutherford*, 2008).
Top-down models adopt an economy-wide perspective taking into account initial market distortions, pecuniary spillovers, and income effects for various economic agents such as households or government. Conventional top-down models of energy-economy interactions have a limited representation of the energy system, as a consequence, they usually lack details on current and future technological options which may be relevant for an appropriate assessment of energy policy proposals. (*Böhringer and Rutherford*, 2008). Typically, as the com-

plexity of the description increases, computational efforts arise. This brings to many energy models focusing on particular aspects or to a specific location. (*Jebaraj and Iniyan*, 2006).
Focusing on bottom-up models, which adopt a more detailed technical description, we can further distinguish at least four subcategories (*Pfenninger et al.*, 2014):

1. Energy systems optimization models: covering the entire energy system, primarily using optimization methods, with the primary aim of providing scenarios of how the system could evolve;

2. Energy systems simulation models: covering the entire energy system, primarily using simulation techniques, with the primary purpose of providing forecasts of how the system may evolve;

3. Power systems and electricity market models: focused exclusively on the electricity system, ranging in methods and intentions from optimization/scenarios to simulation/prediction;

4. Qualitative and mixed methods scenarios: relying on more qualitative or mixed methods rather than detailed mathematical description.

Traditionally these models, given a detailed technical description, tend to aggregate time and space variables, aggregating technologies at national level and considering a small number of time slice per year to reduce computational effort. Examples of established models are MARKAL (*Fishbone and Abilock*, 1981), MESSAGE(*Schrattenholzer*, 1981), TIMES (*Loulou and Labriet*, 2008) and LEAP (*Heaps*, 2008). This choice is no more compatible with the new challenges that energy system is facing nowadays. Due to the increasing penetration of renewable energy source, the energy sector is moving from a centralised production scheme to a highly spatially distributed one with high temporal variability. This leads to a need for high temporal (*Haydt et al.*, 2011) and spatial resolution. In addition, necessity for the amalgamation of planning and operational perspective into a single model are leading to an increased importance of the so-called operational models (*Pfenninger et al.*, 2014), in which the scenarios optimization is no more limited to the yearly energy production distribution among technologies but it is strongly related to daily and hourly production profile.
Finally, some consideration about the advantages of an Open Source Software (OSS) can be done. The free accessibility of these models makes them particularly promising for developing countries and academic applications. It has been shown that OSS can generally meet high standards with little or no difference in quality relative to proprietary software (*Ajila and Wu*, 2007). Dealing

with OSS, we must cite the energy model OSeMOSYS designed to extend the availability of energy modelling to the communities of students, business analysts, government specialists and developing country energy researchers (*Howells et al.*, 2011). An application of the model can be seen in *Welsch et al.* (2012), where the flexibility and ease-of-use of OSeMOSYS with regard to modifications of its code was used to modelling elements of smart grids.
In this work we will use Calliope, an open source optimization software with high spatial and temporal resolutions which wants to meet the challenges of a developing energy sector. Being also easy to use, with a fast learning curve, it is perfectly suited to our purposes. An example of application can be found in (*Pfenninger and Keirstead*, 2015), where Great Britain power system is analysed under different development scenarios considering costs, emissions and energy security.

Hydropower in energy models

The hydropower production characterisation is typically a weakness of energy models. Accounting for the real natural resource availability is not easy for many energy models due to their structure. If the temporal resolution is reduced to only some time slices in a year, an accurate description is not feasible intrinsically. Complex optimization models like the mentioned MARKAL or TIMES work simply on the basis of hydropower installed capacity, exogenously providing the expected yearly energy produced with respect to historical data. Furthermore, an increasing penetration of renewable technologies in the energy sector highlights the interest on operating models. This leads to the need of a more accurate modelling also of hydropower production with the scope of obtaining an optimization by an operational point of view. This aspects gains more importance if we look at the potential of hydropower plants as storage system to be coupled with variable generation technologies. An example can be found in *Dujardin et al.* (2017), who investigate how the existing large fraction of hydropower and significant pumped-storage hydro capacity in the mountainous regions of Switzerland will potentially provide valuable balancing and ancillary services for the management of intermittent production from PV and wind. Similarly *Gebretsadik et al.* (2016) in their work develop a reliability assessment method of wind resource using optimum reservoir target power operations that maximizes the firm generation of integrated wind and hydropower.
Many others attempts of implementing a better hydrological description into energy scenarios can be found in literature for specific case studies analysis. A

different situation is for energy models on wide scale. They are indeed related to huge computational efforts, meaning that increasing the temporal scale and introducing hydrological constraints could be computationally challenging. A modelling solution which try to overcome this issue is the interaction between the large-scale energy model LEAP with the hydrological model WEAP, in the so-called "Soft integration" approach, which will be discussed in section 2.3.2. In addition, the non-linearity of many hydrological phenomena sharpens the modelling challenge.
A first attempt in improving the description of hydropower plants in Calliope energy model has been done by *Good* (2019) for a single reservoir system: the strategy for daily to seasonal balancing of the energy grid of Switzerland was investigated introducing a first improvement in the hydropower plants description.

Focus on the study area

Regarding application on our study area, we can mention the work presented by IRENA (*Miketa and Merven*, 2013), in which the Southern African Power Pool was modelled exploiting the energy model SPLAT, based on MESSAGE. In its work, IRENA evaluates the most affordable investment required by the power generation sector also in terms of domestic and international transmission in order to meet SAPP growing energy demand. This work represents a perfect example in which hydropower is described simply providing the expected energy production in a year without accounting for water resource availability.
Concerning OSS, an application of OSeMOSYS is described in *Taliotis et al.* (2016), where the whole African continent is modelled as a unique energy grid to be optimized showing that an enhanced grid network can alter Africa's generation mix and reduce electricity generation cost. Similarly to our aim, an integrated approach has been explored in *Carlino* (2018), where the original version of OSeMOSYS is expanded to include the main hydrological constraints and reservoirs dynamics. Then, the customized version of OSeMOSYS is coupled with a Water Resources Optimization Model (WROM) to evaluate what benefits can derive via soft integration for both the energy and hydrological systems.

2.2 Hydropower and hydrological models

Hydropower exploits water flows to generate electricity, while also serving as a major source of global energy storage. Hydropower's water management

varies depending on a range of factors such as technology type (reservoir versus run-of-river), reservoir size, climate, engineering and amount of demand from end-users (such as agriculture and recreation). Thus water resource availability and consumption is highly site-specific and the management methodology is widely discussed (*IEA*, 2016). A basin-scale approach can potentially yield more comprehensive solutions for sustainable hydropower, improving the sustainability of both regulatory of existing dams as well as the planning of future dams in regions undergoing the expansion of water management infrastructure (*Hussey and Pittock*, 2012).
In this thesis we will focus on hydropower management problem and we will implement the nexus approach using this source of energy as the fundamental link between water and energy systems. Water management is generally formulated as an optimization problem of a hydrological dynamic system; it is a "wicked" problem (*Reed and Kasprzyk*, 2009) due to the multiple sources of complexity that characterize it:

- The presence of multiple stakeholders results in a multiple objectives problem formulation;
- The phenomena (both in objectives and constraints) involved are described using non-linear equations (e.g. hydropower production is the product of the two decision variables hydraulic head and release from reservoir);
- Intrinsic uncertainty affects the management (e.g. the water availability is not known a priori).

For what concerns the connections with the energy system, it is important to state here that water management requires exogenous input data about the energy demand that should be used as a target. This parameter might also be varying on the time horizon considered, but it is usually defined with a lower temporal resolution than the typical hourly demand profile. Furthermore, in hydrological models hydropower production is an objective function to be maximized without considering energy grid constraints. An example is given by *Turner et al.* (2017), where the turbine release decision is modelled faced by the human operators of each dam as an optimal control problem, whose objective is to maximize the total energy produced by the dam over the long term depending only on storage level and inflow; the only energy production constraint was given by hydropower installed capacity. A more accurate hydropower dependance on energy market has been implemented by *Giuliani et al.* (2014): here the objective function to be maximized is the hydropower revenue depending both on power production and on hourly energy price, de-

fined by the 7h moving average of historical energy price trajectory.
Hydrological models are usually developed specifically for the case studies considered but there is also availability of commercial (as WEAP, (*Stockholm Environment Institute (SEI)*, 2018) and free software (as FREEWAT (*FREEWAT*, 2018)). The considerations made above may vary depending on the level of detail we want to achieve: if the aim is to study long-term large-scale scenarios' future effects, this level of detail may be hard to implement for computational reasons.

Focus on the study area

Efforts are being made among scientists in order to face hydrological modeling challenges such as non-linearity, multiple objectives and stochasticity.
Focusing on the area of interest, pioneers as *Gandolfi et al.* (1997) used a linear network algorithm to optimize only hydropower production. More complex problem formulation has been reached more recently in *Tilmant et al.* (2010), where stochastic dual dynamic programming is used to optimize the system with respect to hydropower production and environmental flow constraints. Concerning basin multiple stakeholders, agent based models (where countries optimize with respect to their own objectives) were used to asses the value of information exchange in the basin, similarly to the real case, as opposed to fully cooperative optimization with interesting results in *Giuliani and Castelletti* (2013).

2.3 Water-Energy models

As we have seen so far, there are deep differences between energy and hydrological models:

- In energy models the spatial scale is often political and therefore it rarely overlaps with hydrological basin boundary;
- In energy models the time resolution has to match with the electricity market, i.e. the hourly energy demand, or long-term interannual economic analysis, while in hydrological models the time resolution follows the basin dynamic and seasonality;
- In energy models hydropower is modeled under the assumption of hydrological stationarity, neglecting water resource variability and uncertainty, which are the core of hydrological models;

- In hydrological model, the energy system is not considered in its entirety and hydropower production is usually maximized without considering energy grid.

In tab.2.1 is resumed how hydropower and energy grid are implemented in the energy and hydrological models above mentioned. To implement the nexus approach these differences in methods and models have to be overcome. This means that several tradeoffs have to be made between different modeling assumptions (e.g. spatial and temporal resolution). It may result in less detailed or smaller sized problem, but will surely lead to new interesting results connecting water and energy systems. These connections can be explored with three different approaches: no integration, soft integration and full integration.

Table 2.1: *Energy and hydrological models comparison.*

Aggregated storage technology: possibility to define a single storage technology for a region aggregating the overall storage capacity. **Input data from WEAP**: hydropower production evaluated by the hydrological model WEAP maximizing water demand according to given priorities. **Input data from LEAP**: the overall amount of energy production which requires water for cooling systems.

Model	Open Source	Time resolution	Hydropower modelling	Energy grid modelling
MARKAL, MESSAGE, TIMES	✘	timeslice	Installed capacity, capacity factor, aggregated storage technology	✓
OSeMOSYS	✓	timeslice	Installed capacity, capacity factor, aggregated storage technology	✓
Calliope	✓	hourly	Installed capacity, exogenous conversion efficiency timeseries, exogenous resource timeseries, storage technology	✓
LEAP	✘	timeslice	Installed capacity, capacity factor + input data from WEAP (hydropower production)	✓
WEAP	✘	timeslice	Rainfall runoff inflows, evapotranspiration, additional water demand, surface water/groundwater interaction	input data from LEAP (energy production requiring cooling water)

2.3.1 No integration

Historically, the energy and water systems have been considered separately because of the high computational cost of integrating these two models. This is indeed the simplest and the first approach considering the effect of one system on the other. Within this approach, the interdependency between energy and water systems is indirectly taken into account through the input variables employed in each one of these two models. For instance, energy data (e.g. energy demand) can be given as input to the water system model, whose water allocation strategy among different users (e.g. hydropower) will then be assessed. On the other hand, hydrological data (e.g. inflow pattern) can be fed into the energy system model for determining hydropower production. This methodological procedure is outlined in fig.2.1.

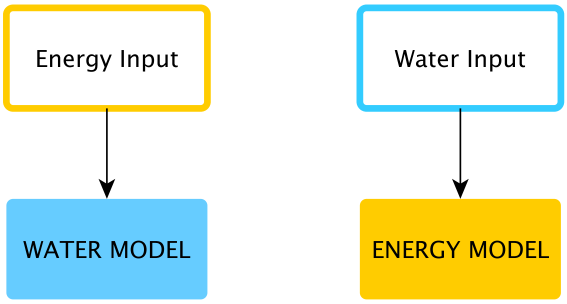


Figure 2.1: *No integration scheme for energy and water systems modeling.*

This approach was used by *Voisin et al.* (2016), who coupled a water model (representing climate, hydrology, water resources management and socio economic constraints) with an electricity production cost model to finally simulate energy generation and power delivery. Here the hydrological model first computes the hydropower production and water availability for thermal cooling over the time horizon, then the production cost model optimizes the energy system constrained by these water inputs. With this model was possible to assess the linkages among water availability and unserved energy and the value of inter–regional power grid coordination, especially during extreme events. The work was then extended in 2018 focusing on the effect of climate teleconnections on energy grid on the west coast of United States. Results showed that management accounting for ENSO oscillations would result in more reliable energy grids as water availability is highly dependent on these phenomena (*Voisin et al.*, 2018).
Advantage of this approach is in its low computational demand so it can be applied for large scale system. On the other side, disadvantages are in the absence of dynamic interaction between the water and energy system.

2.3.2 Soft integration

A second approach is represented by the so-called "soft integration" procedure shown in fig.2.2. With this method, the two models are still separate but, working cooperatively in a loop where they exchange information, they may eventually converge to a solution satisfying the two systems. The important concept behind soft integration is that each model is based on its own objectives and components but, via information exchange in each cycle, the effect of the one on the other is recursively evaluated and managed by the successive runs.

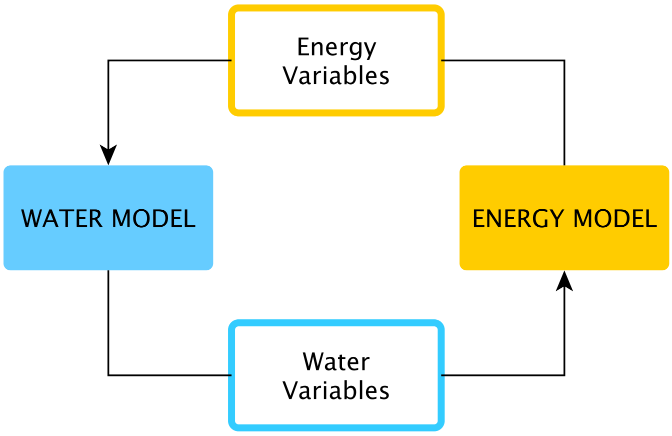


Figure 2.2: *Soft integration scheme for energy and water systems modeling.*

This was applied in *Fernandez-Blanco et al.* (2016), who presented a water-energy model framework developed by the Joint Reserach Centre of the European Commission. The model uses linear programming to describe the hydropower component and the power dispatch dependent on reservoirs' releases for plant cooling. Soft integration was also used by *Pereira-Cardenal et al.* (2016) in improving hydropower sector description for the Iberian Peninsula. Results show the benefits of an explicit hydropower reservoir definition since exploiting multipurpose reservoir and different catchment characteristics improves each river basin productivity in hydroelectric or irrigation terms. Another example of soft-integrated hydropower representation is given by the interaction between the energy model LEAP and the water model WEAP. WEAP evaluates water supply to hydropower accounting for water demands priorities; the resulting hydropower production is provided exogenously as input to LEAP. This approach has been applied In *Agrawal et al.* (2018) to evaluate the long-term impacts of climate change scenarios on water requirements and greenhouse gas (GHG) emission in the western Canadian province of Alberta.
Advantages of this method consist in the fact that pre-existing models (encoded in different programming languages too) can be employed, since the water and energy system models are kept separate. At the same time it is not always easy to identify where the link among the two systems has to be put in place and what is the related most effective mathematical description. In addition to that, this approach can work well if the two models really converge and it is not

easy to predict whether this approach will lead to such a result and how many iterations this might take.

2.3.3 Full integration

Another option is to build a fully integrated water-energy model as depicted in fig.2.3. The idea of this approach is to describe in a single model both the systems making explicit their conflicts and synergies. The joint optimization will then consider, according to the objective functions defined, how to allocate the resources in the two systems and how to balance the tradeoffs deriving from such a complex problem.

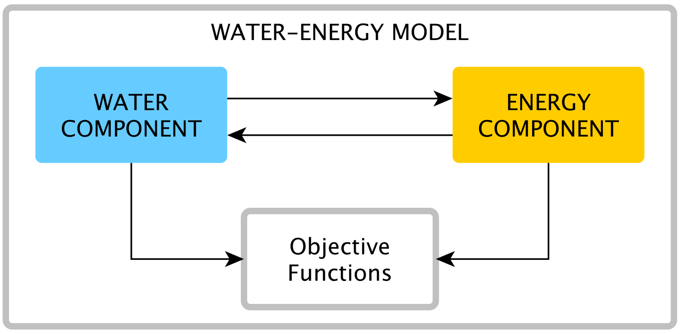


Figure 2.3: *Full integration scheme for energy and water systems modeling.*

This is how *Bertoni et al.* (2016) evaluates the connection among overall energy production and cooling water for thermal plants in the Iberian Peninsula. The scenario with effects of climate change made explicit all the conflicts among water for energy (hydropower production decline due to low inflows), increase in thermal energy production (to fill the gap of hydropower) and the irrigation deficit (water consumptive use and low inflows reduce water availability to farmers). Similarly *Khan et al.* (2018) built a fully coupled water-energy optimization model which hard-links the two systems in detail across spatial and temporal scales, as well as between individual system processes throughout the life-cycle of each resource. This insight provides the opportunity to build a more robust system which is shown to lower costs, improve efficiency and increase the security of supply across a range of variations in several uncertain parameters such as resource demands and precipitation.
Many advantages derive from a joint modeling and optimization of water and energy systems. Indeed their effect on each other and the respective contribution for managing the two systems are adequately considered, with no approximation in the dynamic functioning as the two systems react to each other.

Even though this would be the perfect approach, there are disadvantages. At present, a model where water resources management and energy system planning and management are optimized simultaneously, with the level of detail required by the complex phenomena involved, has not been implemented yet because of its high computational cost. However, by balancing computational effort and model accuracy, this procedure can be followed and used also for large spatial and temporal scale.

3 Methodology

In this chapter we explain our integrated modelling strategy. We use Calliope, a free and open source optimization linear programming energy model. The high spatial and temporal resolution combined with the freedom of defining easily new technologies makes Calliope perfectly suited to overcome the modelling weaknesses of hydropower.
After a general description of Calliope features (section 3.1), in section 3.2 we first describe the modelling solution adopted for implementing all technologies without hydrological constraints in the model named *Calliope_base*. Then section 3.3 is dedicated to how we integrated hydrological constraints building the water-energy model *Calliope_hydro*.

3.1 Calliope

Energy system models allow analysts to build scenarios of how energy is extracted, converted, transported and used providing as results the optimal operational condition. For our work we decided to use Calliope modelling tool. Calliope is a free and open-source optimization linear programming model focused on flexibility with high spatial and temporal resolution. It was design with the following goals in mind (*Pfenninger and Pickering*, 2018):

- Designed from the ground up to analyze energy systems with high share of variable generation;
- Formulated to allow arbitrary spatial and temporal resolution, and able to deal with time series input data;

- Simplify the definition and deployment of large numbers of model runs to high-performance computing clusters;
- Generic technology definition allows modelling any mix of production, storage and consumption;
- Uses a state-of-the-art Python toolchain based on Pyomo, xarray, and Pandas;
- Have a free and open-source code base under a permissive license.

From users' point of view, we highlight that Calliope has a clear separation between the framework (code) and the model (data); it makes building a model very simple without requiring a deep programming knowledge.
A model based on Calliope consists of input text files (yaml and csv format) defining technologies, locations and resources of the scenario under analysis. Calliope builds and solves an optimisation problem on the basis of user's input. The objective function is the minimization of total system costs for a specific cost class or a set of cost classes (monetary, emissions, etc.). Results can be easily analysed by Calliope built-in-tools.

Building a model

Calliope uses the power nodes modelling framework (*Heussen et al.*, 2010), in which each location is described as a point of a network, with its own technologies and demands to be satisfied (power demand, heat demand, etc.).
In short, we can resume the following features available to implement a system description:

- **Supply technologies** to produce a specific energy carrier, having also the possibility to take an input resource;
- **Transmission technologies** to move energy from one location to another;
- **Conversion technologies** to convert one carrier into another;
- **Storage technologies** to store energy removing it from the system.
- **Demand technologies** to consume a carrier from the system.

In more technical terms, Calliope allows a modeller to define technologies with arbitrary characteristics by "inheriting" basic features from a number of included base tech groups (i.e. *supply, supply_plus, conversion, conversion_plus, storage, transmission* and *demand*). Thanks to the possibility of defining many carriers and many power demands, Calliope can be used for a wide analysis of the energy system. In our specific case, we focus only on the electricity sector.

3.2 *Calliope_base*

In this section we briefly depict which are the traditional modelling strategies for describing all technologies present in an energy system. We aim to present the rational on which *Calliope_base* was built since it is used as benchmark for the analysis of *Calliope_hydro* results (for further details about the Calliope model see the online documentation[1]). The description of an energy system can be expressed by listing the technologies present in a given scenario and by defining the locations on which they are located. For the technologies description, the modeller must specify some essentials characteristics and some technical and economic constraints. The essentials are used to provide a name, to specify the technology group and to set the carriers with which the technology works. The technical and economic constraints are then defined to characterised specifically the peculiar behavior of each model component:

- **Technical**: lifetime [years], installed capacity [kWh], conversion efficiency, ramping rates, etc.
- **Economical**: fixed costs [$\kW] (e.g. capital costs), variable costs [$\kWh], cost of the fuel [$\kWh], interest rate, etc.

Starting from this general scheme, each technology can be depicted by taking advantage of the appropriate Calliope modelling features.

Fossil fuels, nuclear and biomass

All fossil fuel plants are described like *supply* technology with an infinite resource exploitable. This choice is coherent for scenarios in which we are not interested in the analysis of fuels production, conversion, extraction and transportation and assuming a continuous supply of fuels like coal, natural gas or diesel. A fully description is then achieved by providing just technical and economical constraints. Nuclear and biomass power plants are modelled similarly, assuming an infinite resource availability.

Renewables

Renewable technologies are typically strictly related to resource availability. Photovoltaic and wind power plants need to be modelled accounting for this variability. Adopting the *supply_plus* default configuration we can provide as input the timeseries of potential electricity production for a given location (alternatively one can provide wind power or solar irradiation as input timeseries

[1] `https://calliope.readthedocs.io/en/stable/`

completing the description with the appropriate conversion efficiencies and power capacity).

Hydropower

In the base version of our model, *Calliope_base*, the description of hydropower plants operation is equal to the one discussed for fossil fuels plants. Hydropower is implemented like a *supply* technology without accounting for resource availability. This means that it has the freedom of exploiting always the overall capacity and its operation is influenced only by economical constraints and not by hydrological ones. Such a description does not consider the presence of the water storage system and it doesn't account for the connection among cascade reservoirs. Here stands the main difference between *Calliope_base* and *Calliope_hydro*, in which an advanced modelling strategy is implemented on reservoirs for which hydrological data are available.

Electric transmissions

Electric transmissions between different locations are fundamental in modelling multiple nodes scenarios. In addition, the *transmission* technology gives the possibility of assigning a cost and an efficiency dependent on transmission length.

Power demand

Calliope optimization aims to cover the power demand of each node of the energy network minimizing system costs. The power demand can be defined up to the hourly timestep thanks to Calliope flexibility in defining spatial and temporal resolution. The higher the spatial and temporal resolution the higher the accuracy of the optimization. The limit is the level of detail of available data, since the power demand hourly profile should be defined for each node.

3.3 *Calliope_hydro* hydrological constraints

In a scenario with high share of hydropower production, modelling this technology in a realistic way becomes a key problem. A fully description of a hydropower plant should take into account the reservoir hydrological dynamic in terms of:

- Water availability related to inflow patterns;

- Dam maximum and minimum operational level;
- Maximum and minimum release constraints;
- Evaporation losses dependent on reservoir surface;
- Time-variable hydraulic head dependent on reservoir level;
- Cascade release of multi-reservoirs systems.

A description based only on the installed capacity is not exhaustive because hydropower production is inherently linked to water availability and basin-scale reservoir dynamic.
Some works, as *Good* (2019), tried to take into account water resource by providing the model the real operation timeseries of plants in terms of energy produced; in presence of a dam, a *storage* technology was added to allow the model to store hydroelectric energy in the reservoir. Anyway, this approach neglects most of the hydrological constrains listed above.
Our modelling strategy is designed to overcome this weakness. A multiple cascade reservoirs model is built exploiting the potentiality of Calliope. Each water storage is modelled including a description of the maximum release and providing the real water availability through inflow trajectories. Additionally, an external loop is built to account for time-variable hydraulic head dependent on reservoir level and evaporation losses dependent on reservoir surface. The overall scheme of our integrated modelling strategy is illustrated in fig.3.1.

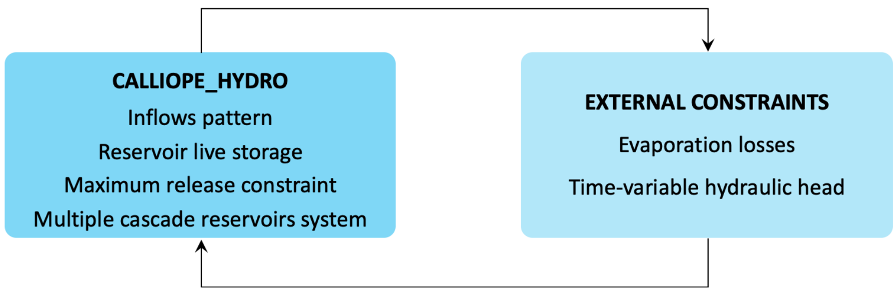


Figure 3.1: *Scheme of hydrological constraints implementation.*

3.3.1 Multiple cascade reservoirs

Building a system of cascade reservoirs means implementing a modelling solution in which the release from the upstream water storage is traced as inflow to the downstream one. In this section we describe how we implement this solution dealing with two reservoirs; the modelling strategy can be extended to a n-reservoirs system. The model configuration is shown in fig.3.2.

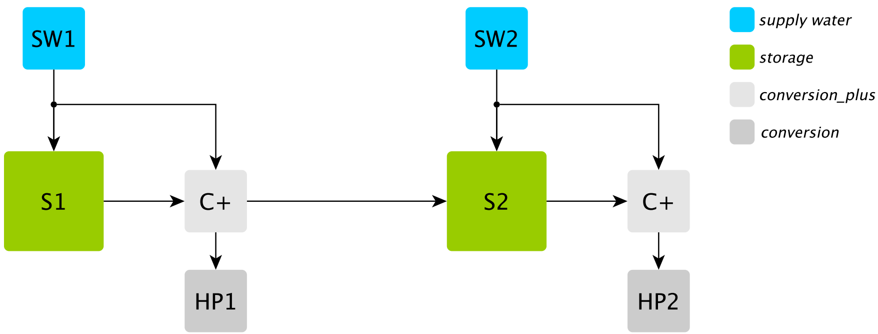


Figure 3.2: *Multiple cascade reservoirs system configuration.*

For describing the reservoir itself, called "S" we use the *storage* technology defining its main characteristics: storage capacity, storage level at first time step and maximum water release (i.e. the maximum flow which can be turbined). The storage capacity is defined referring to the live storage, namely the capacity between the reservoir maximum level and the minimum operational one at which water can flow through turbines. Alternatively, exploiting the latest updated version of Calliope, we can provide the storage maximum capacity and set a deep of discharge accordingly to the real water level limits. The choice of the initial storage level gives the modeller the freedom of exploring a broad possibility of different scenarios. Furthermore, the user can set the condition of cycling storage, meaning that at the final time steps the storage level is equal to the initial one. To further increase the hydrological dynamic accuracy, we customized Calliope original code decoupling the initial storage state with the final one. It allows to start the simulation in dry conditions or at full capacity but imposing an arbitrary final storage value, e.g. as close as possible to the optimal operational one.
The component called *water supply* technology (SW) represents the inflow, defined as the waterflow entering the storage from precipitations and tributary rivers but not accounting for the water released by an upstream reservoir. The *supply* technology is perfectly suited to our needs as it takes as input an exogenous resource timeseries (i.e. the water available) giving the possibility of forcing the model to use it entirely.
The technology that brings in input the water outflow from the storage and transform it into electric energy is properly a *conversion* technology (HP), representing the typical operation of a hydropower plant. The conversion is performed through an efficiency coefficient that transforms the potential energy of

water into electricity, computed as follow:

$$\eta = \rho * g * head * \eta_{turbine} * \frac{1}{3600} \tag{3.1}$$

with $\rho = 1000\,kg/m^3$ water density, $g = 9.8\,m/s^2$ acceleration of gravity, $head =$ geodetic hydraulic head $[m]$ available at the plant, $\eta_{turbine} =$ turbine efficiency, and finally 1/3600 is the conversion coefficient necessary to express the electric energy in kWh.
In the scheme reported can be seen how the above described technology is not directly linked with the storage. The presence of a *conversion_plus* technology (named "C+") is crucial to connect the two water systems, because when the *conversion* technology (HP) converts the inlet resource (i.e. water) into a new carrier (i.e. electric energy), the resource in input is not available anymore, coherently with what happens for instance in a power plant run with fossil fuels. Hydropower plants work differently, and water release must be still trackable after power production in order to flow into the downstream reservoir. The *conversion_plus* technology (C+) supports several carriers in input and several carriers as output and the freedom of imposing a different conversion efficiency for each carrier. The possibility of having multiple outputs allows us to "duplicate" the water release, making one stream go into the hydropower plant (HP) to produce electricity and making the twin-stream flow into the cascade reservoir.
This modelling structure gives also the possibility of connecting two reservoirs in different nodes or, in case of transboundary reservoirs, modelling multiple hydroelectric power plants in different locations. To fully implement such systems, a *transmission* technology is required. In Calliope, the *transmissions* allow to exchange the same carrier between different nodes. This is valid both for electric transmission lines and for waterflows crossing different locations. In the case shown in fig.3.3 a water transmission line is set, mimicking rivers.

Reservoir water mass balance

In this section we verify if the system mass balance respects the hydrological dynamic. Indeed, looking both at fig.3.2 and fig.3.3 we can notice a row exiting from the *supply water* technology (SW) and entering directly in the *conversion_plus* one (C+) skipping the reservoir. Actually in real systems all the inflow enters the reservoir before being released to the hydropower plant; it is important to explain why this stream is present and to understand if it moves our description away from the real physical dynamic.
First, we have to highlight that Calliope model itself intrinsically creates the

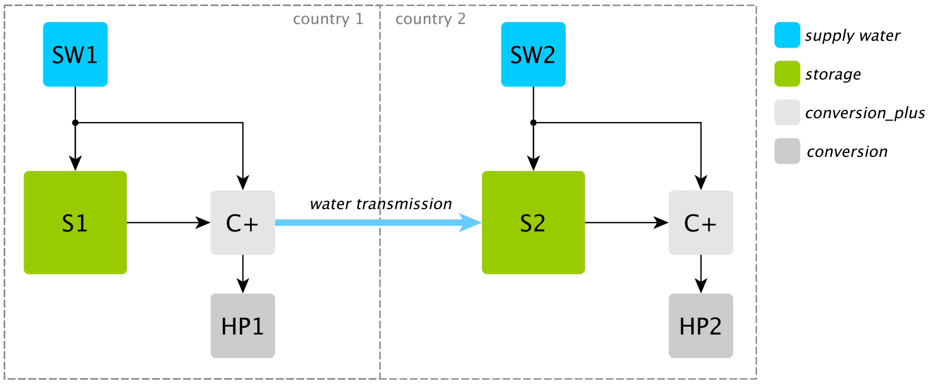


Figure 3.3: *Multiple cascade transboundary reservoirs system configuration.*

links between technologies that work with the same carriers. In our case the carrier output of SW is the same carrier input of S1 and C+, this is why they are all linked.
Secondly, we can assert that this configuration is not undermining the hydrological description. Considering the high temporal resolution of our simulation with hourly timesteps, the amount of water skipping the reservoir is consumed almost instantly, and its influence on the reservoir mass balance is negligible. Reservoir dynamic is thus preserved: an excess of inflow will be still stored in the *storage* technology while the *conversion_plus* one will be still able to draw water from the reservoir to satisfy hydropower production.
To prove the reliability of this model, we compared the multiple reservoirs configuration applied to just one storage with the single reservoir configuration. Results overlap showing the equivalence of the two systems schemes (details in appendix A).

The spillage

So far we described and modelled a hydrological reservoirs system which differs from the real one of an important design component: the spillage. The spillway of a dam is a gateway from which the water is released skipping the turbines; the spillage occurs in case of full reservoir, when the water level reaches the maximum operational level of the dam. In case of optimized reservoir management, this could happen only if water inflow exceeds the storage capacity.
A water-energy model should be able to manage inflow peaks or flood events, so it should be able of activating the spillways. The latest updated version of Calliope does not provide a modelling component which is able to be activated when given conditions occur, e.g. when the storage reaches its maximum ca-

pacity. Defining a new technology would have required a deeper programming knowledge, straying beyond our aims. For this reason we model the spillage as a *conversion* technology connecting two cascade reservoir with a conversion efficiency equal to zero (that's why in fig.3.4 the row connecting the spillage and S2 is dotted).

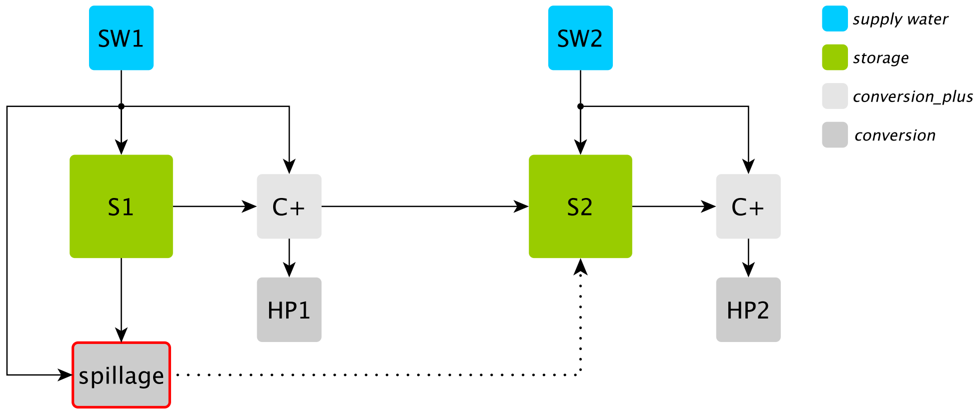


Figure 3.4: *Spillage implementation in multiple cascade reservoirs system configuration.*

We made this choice because a non-null conversion efficiency allows the model to allocate water arbitrary from upstream to downstream reservoir following an economical optimization. Setting the efficiency equal to zero, the spillage is modelled as a wasted water flow in order to be minimized by Calliope optimization. The modelling scheme proposed ensures a solution for each scenario, but the water spilled never reaches the downstream reservoir. For this reason the most reliable results are the ones in which spillage is never activated, with a fully respect of the reservoirs water mass balance. The activation of spillage introduces an error in the model solution, which has to be carefully evaluated to understand how much it affects results.
The aim of this work is providing a very first water-energy modelling approach exploiting existing Calliope modelling components. This is the reason why we chose to implement the spillage despite of drawbacks: to suggest how implementing and improving its description in future development while ensuring a solution for every inflow scenarios.

Water demand

In order to conclude the section dedicated to modelling reservoirs, it is important to highlight that completing the system with a water demand (e.g. for irrigation) is unnecessary for our purpose, but it would be feasible to implement accordingly to a specific case study. Exploiting the flexibility of Calliope by including also non-monetary cost (e.g. for unmet hydropower production due to water demand supply) could widen the system analysis, optimizing the scenario for multiple objectives (e.g. hydropower production and water deficit).

3.3.2 External loop implementation

We illustrated a multiple cascade reservoirs configuration. What the hydrological dynamic is missing are the storage losses due to evaporation and the definition of the time-varying hydraulic head, both dependant on the storage. There is no technology in Calliope able to define such dependencies between variables at each time step of the simulation, neither it would be possible to further develop such a feature because problem linearity would be compromised. In this section we describe how we account for evaporation losses and time-varying hydraulic head in an external loop which interacts with Calliope storage timeseries, inspired by the work of *Del Pero et al.* (2019).

Evaporation losses

The evaporation of water stored in a dam could be an important source of losses in some case studies, especially for very extended reservoirs in tropical climate zones. Calliope provides a predefined constraint which allows to define a storage loss as a fraction of total capacity per hour (also in the form of timeseries). In this way we can evaluate storage losses due to evaporation at each timesteps and provide it to Calliope as an input timeseries.
Once evaporation losses are evaluated as a function of reservoir surface thanks to the net evaporation coefficient (eq.3.2), the storage losses timeseries are computed as in eq.3.3:

$$evap\_loss_t \left[\frac{m^3}{h}\right] = evap\_coeff_t \left[\frac{m}{h}\right] * surface_t \, [m^2] \tag{3.2}$$

$$storage\_loss_t = \frac{evap\_loss_t \, [m^3/h]}{storage\_capacity \, [m^3]} \tag{3.3}$$

where $evap\_coeff_t$ is a time-varying parameter accounting for seasonal variation of the net evaporation. The $surface_t$ is function of the storage but it cannot be provided directly by Calliope; this introduces the necessity of some calculation performed externally to the model.
Since we can extract the storage timeseries from Calliope, the reservoir surface at each time step can be easily computed once hydrological data about its *storage-surface curve* are known. Here an issue arises: the storage timeseries is

a result of the optimization process, so it can be extracted at the end of simulation. Consequently, storage losses implemented in a new iteration are computed on the basis of storage timeseries of the previous optimization. This is the reason why we implement an external loop. In the initialization phase, the model is run without accounting for evaporation losses. Then the storage timeseries is extracted and the evaporation losses evaluated for each timestep. These losses are provided to Calliope as storage loss timeseries and a new optimization is run. The loop restarts in an iterative process for a given number of iterations; the goal is reaching convergence, namely obtaining the final storage timeseries equal to the one at the previous iteration.

The hydraulic head

When the storage level variation is of the same order of magnitude of the overall hydraulic head it may influence the hydroelectric conversion efficiency. In section 3.3.1 we explained how hydropower technology converts the water flow into electricity thanks to an efficiency coefficient dependent on the hydraulic head (eq.3.1). The conversion efficiency can be provided in Calliope as an input timeseries, giving us the possibility to take into account time-varying hydraulic head.

The hydraulic head is function of the storage level, thus of the storage volume. Similarly to evaporation losses, it can be easily evaluated once hydrological data about reservoir *storage-level curve* are known. In order to compute the conversion efficiency timeseries dependent on time-varying hydraulic head, we implement the same external iterative process adopted to evaluate storage losses. The complete external loop implementation is illustrated in fig.3.5.

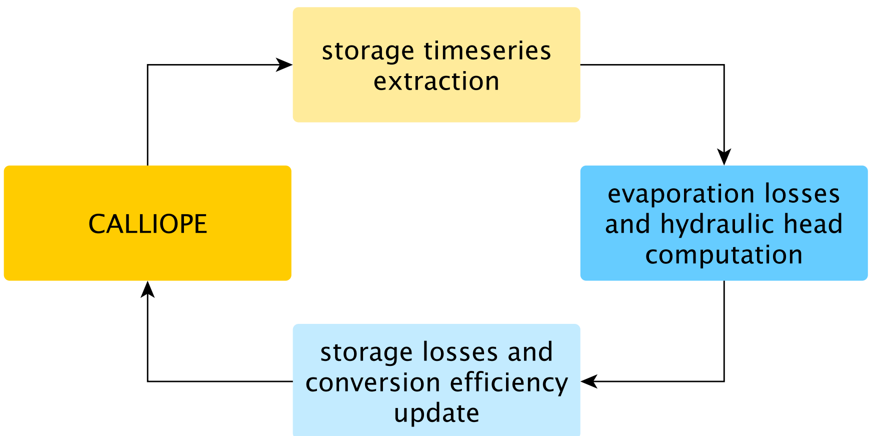


Figure 3.5: *External loop implementation.*

4

Case study

4.1 The Southern African Power Pool

The SAPP was created in August 1995 at the Southern African Development Community (SADC) summit, when member governments of SADC signed an Inter-Governmental Memorandum of Understanding for the formation of an electricity power pool in the region under the name of the Southern African Power Pool (*SAPP*, 2018). The country members of SAPP are: Angola, Botswana, Democratic Republic of the Congo, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, United Republics of Tanzania, Zambia and Zimbabwe (fig.4.1).
One of the SAPP main objectives is providing a forum for the development of a world class, robust, safe, efficient, reliable and stable interconnected electrical system in the southern African region with the aim of ensuring the least cost, environmentally friendly and affordable energy while increasing accessibility to rural communities (*SAPP*, 2018). In addition, sustainable energy is at the forefront of the development plans of African nations, recognising its central role in achieving all SDGs targets and mitigating and adapting to climate change. Sustainable development and use of the continent's massive biomass, geothermal, hydropower, solar and wind power have the potential to rapidly change Africa's current realities (*IRENA*, 2019). As *Hadebe et al.* (2018) highlitghs, Africa has immense untapped renewable energy potential; yet, the continent remains largely dark with over 600 million people in sub-Saharan Africa without access to energy. Only 43% out of a population of 177 million in the

Figure 4.1: *The Southern African Power Pool countries (source: UNESCO-SADC (2017)).*

Southern Africa region have access to electricity, ranging from 85% in South Africa to 40% in Zimbabwe and 9% in Malawi. For the remaining countries, the rates of electrification range from 40 to 15% (*Ouedraogo*, 2017).
The total installed capacity in the SAPP is 50 GW which generates around 400 TWh of electricity, but the regional demand is expected to increase 4.5 times by 2040 up to 1061 TWh. Despite coal-fired power dominates the regional power mix (fig.4.2), nearly 40 GW of hydropower could be potentially deployed in the short to medium term in order to meet such an increasing power demand (*Ouedraogo*, 2017). Hydropower will thus play a key role in the future power generation mix as well as at present. Individually many SAPP members are already strongly dependent on hydropower production: Zambia and Mozambique rely on hydro for 80% of their electricity generation, also exporting their hydroelectric energy, while Zimbabwe hydropower accounts for up to 60% of the total production.[1].
Further hydropower development is already underway. SADC has identified four hydropower plants as priority areas: the Mpanda-Nkuwa in Mozambique, the Inga III in the Democratic Republic of Congo, the Batoka Gorge project between Zambia and Zimbabwe, and the Lesotho Highlands Water Project Phase II. These projects, along with other small hydropower systems, are expected to meet the region's renewable energy requirements as SADC intends to in-

[1]Data source: `https://www.iea.org`

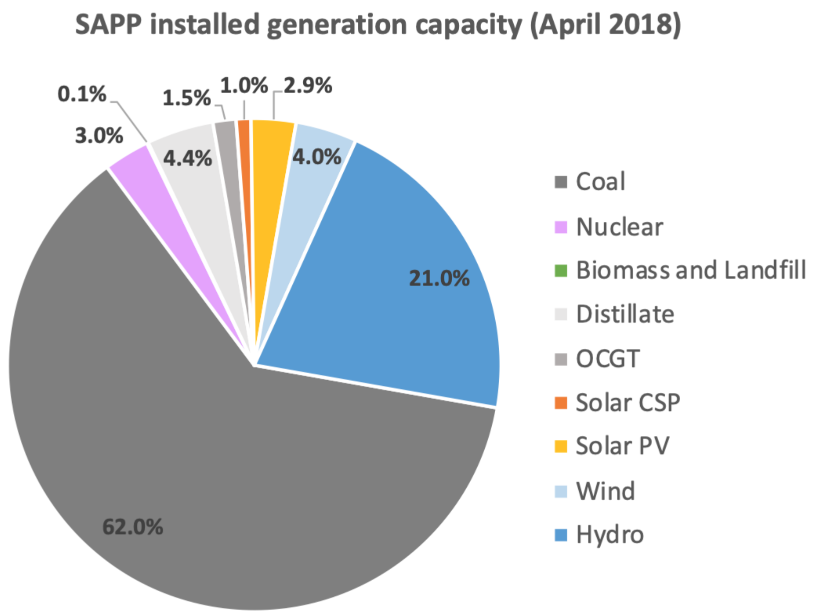


Figure 4.2: *SAPP installed generation capacity (source: SAPP (2018)).*

crease the share of renewable energy to 33% by 2022, and 37% by 2027, in pursuit of the goal of 100% renewable energy by 2050 (*SADC*, 2020). Due to the relatively low cost of hydropower and the high load factors, hydropower is strongly identified as the cost-effective way to rapidly increase renewable energy uptake (*Hadebe et al.*, 2018) and to offer a sustainable alternative to the fossil fuel electricity generated in the SAPP.

4.2 The Zambezi River Basin

The Zambesi River Basin (ZRB) biophysical and hydrological context are taken from *The World Bank* (2010) and *Beilfuss* (2012). The Zambezi River lies within the fourth-largest basin in Africa. Covering approximately 1.4 million km^2, the ZRB is the largest basin in Southern Africa extending across Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe. The Zambezi River, with a total length of 2,574 km, originates in Zambia at 1,450 m above sea level and flows south-eastwards to the Indian Ocean. The Kafue River, which rises in northern Zambia, is the major tributary.

The ZRB has one of the most variable climates of any major river basin in the world, with an extreme range of conditions across the catchment and large intra- and interannual variability. Average annual rainfall is about 960 mm, but varies from more than 1,600 mm per year in the northern highland areas to less than 550 mm per year in the water-stressed southern portion of the basin. Similarly, runoff is highly variable across the basin, and from year to year. Such high hydrological variability makes the entire ZRB highly susceptible to extreme droughts and floods that occur nearly every decade, with considerable impact on river flows and hydropower production in the basin (fig.4.3). The major existing hydropower dams on the Zambezi were indeed designed based on an inadequate time series of inflows to adequately characterize the full range of natural variability experienced over the past century (*Beilfuss*, 2012). As a result, firm power production is vulnerable to periods of prolonged droughts, and dam safety and downstream flood risk is vulnerable to extreme flooding events. For example, during the severe 1991/92 drought, reduced basin hydropower generation resulted in an estimated US$102 million reduction in GDP, $36 million reduction in export earnings and the loss of 3,000 jobs. On the other hand, hydropower operators and river basin managers face a chronic challenge of balancing trade-offs between maintaining high reservoir levels for maximum power production and ensuring adequate reservoir storage volume for incoming floods.

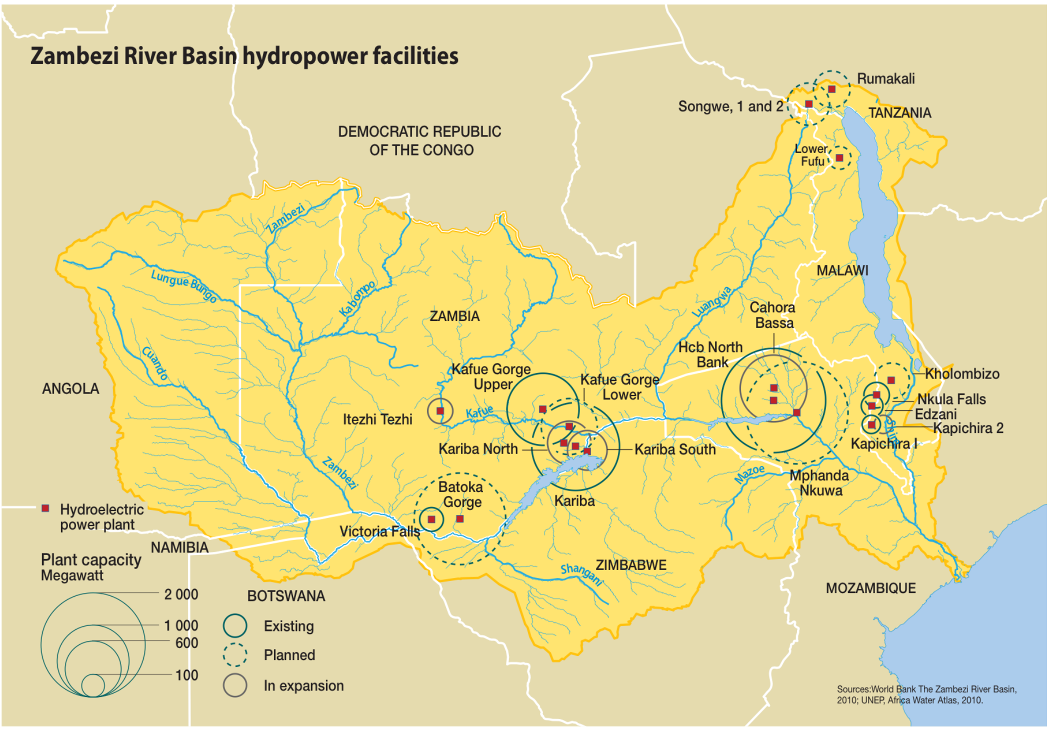


Figure 4.3: *The Zambezi River Basin and its hydropower plants.*

The natural variability of Zambezi River flows is highly modified by large dams, particularly Kariba and Cahora Bassa dams on the mainstem, as well as Itezhi-Tezhi and Kafue Gorge Upper dams on the Kafue River tributary. The most important hydrological conditions for downstream livelihoods and biodiversity, especially the timing, magnitude, duration, and frequency of seasonal flood pulses, have been altered inevitably. Evaporation losses further reduce the water availability in the basin: beside the natural losses that account for about 20% of the precipitation (*Chenje*, 2000), the evaporation from large hydropower reservoirs exceeds 10% of the mean annual river flow. These water losses increase the risk of shortfalls in power generation, and significantly impact downstream ecosystem functions.

Beside meeting the basic needs of about 30 million people in the riparian countries, the Zambezi River also provides important ecosystem services. The Zambezi is essential to regional food security and sustains a rich and diverse natural environment. Home to a rich biological diversity and some of the densest concentrations of wildlife in the world, the Zambezi River Basin features several of Africa's finest national parks and some of UNESCO World Heritage Sites.

In such a rich and complex environmental system, integrated hydropower planning and management is paramount for addressing all the impacts on stakeholders and ecosystems. Existing hydroelectric plants have caused important environmental losses in the basin and are responsible for people displacement. Concerns are increasing in recent years since 13 GW of hydropower potential has been identified in addition to the actual 5 GW of installed capacity.

Finally, the ZRB energy system will be influenced by the projected impacts of climate change, with the Intergovernmental Panel on Climate Change (IPCC) that has categorized the ZRB as exhibiting the "worst" potential effects among 11 major African basins. Over the next century, the ZRB will experience drier and more prolonged drought periods and more extreme floods, increasing the vulnerability of the basin and its hydropower dams.

For all these reasons, our analysis focuses on this basin as part of the overall Southern African Power Pool: except for South Africa, all the other SAPP members rely on the Zambezi River Basin water resources for hydropower production, both in terms of domestic generation and for clean energy import. In this region, hydropower has the potential to accelerate the transition of many countries towards a higher share of renewable generation. Considering the importance of water resources for these countries and the relevance of new projects that may influence the overall energy system, a new approach where hydropower is planned basin-wide while also considering the whole energy system is expected to be particularly valuable.

4.3 Modelling the SAPP

In this section, we describe all the modelling choices done in our work to build the SAPP energy grid. The low availability of data was the main obstacle as we had to search for information from many different energy authorities and many actors involved (from the control of production to the distribution and management of the energy system). In case of no data availability, we statistically inferred some information.
Calliope exploits the power nodes modelling framework, so each node of our network represents an entire country. Since we found more detailed data for Mozambique, this latter was modelled with two nodes, one for the South and one for the North-Center of the country (fig.4.4). On the other hand, some coun-

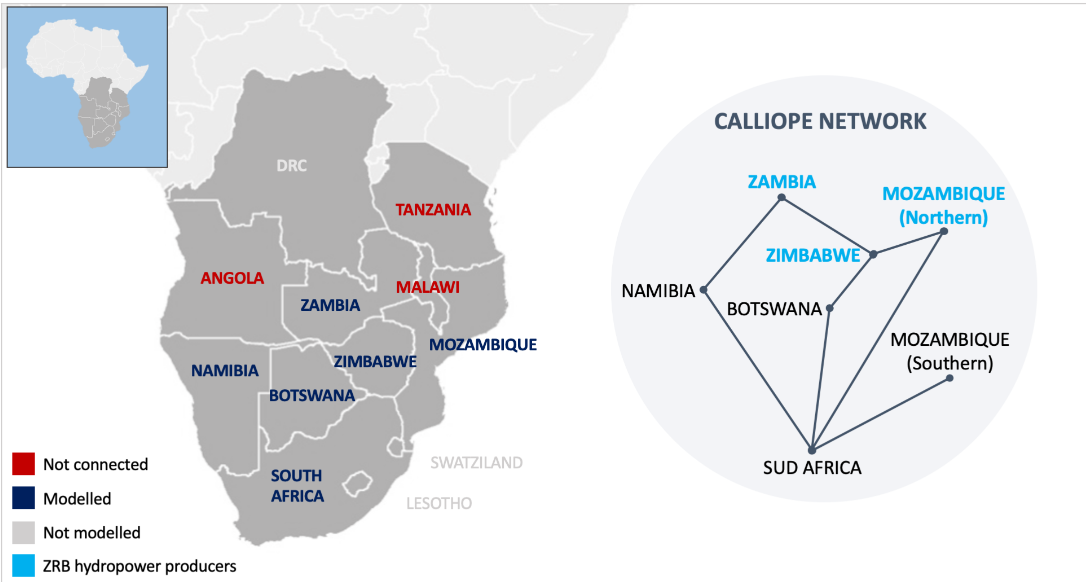


Figure 4.4: *SAPP countries and modelling network.*

tries are not modelled. Angola, Tanzania and Malawi are not connected to the grid and are not part of the Zambezi River Basin; Lesotho and Swaziland are excluded from our network because of their negligible contribution to the energy generation, equal to the 0.32% of SAPP total capacity (*SAPP*, 2018). The Democratic Republic of Congo is also not modelled. Beside the lack of data, the main reason is its high hydropower installed capacity that we could not improve according to the modelling approach introduced in the previous chapter. While we are improving the model for the ZRB plants, including the Democratic Republic of Congo with a standard hydropower representation could reduce the impacts of our new modelling components. It is important to state that this choice is not introducing a significant error in the model. DRC indeed covers

its total energy demand almost relying only on domestic power production, with import and export having the same order of magnitude of the statistical error[2]. Thus we can assert that DRC is almost operating like a not connected country.
What we discussed above leaves space for further development of this work, especially looking at future scenarios with enhanced electric transmissions between countries. Additionally, DRC hydropower integrated modelling will became crucial in the case of realisation of the Inga III and Grand Inga dams (*Green et al.*, 2015).

4.3.1 Power production technologies

In chapter 3, we have listed all the constraints required for technologies modelling. Regarding lifetime, energy efficiency and economical data, we referred to *Miketa and Merven* (2013) and *Wittenstein and Rothwell* (2015).
Concerning installed capacity data for each country, we looked at national energy companies reports. Table 4.1 shows the capacity installed for each country for each different technology[3]. South Africa is the biggest producer and consumer of energy. Its production comes mainly from coal fired power plants, followed by hydropower and nuclear. Zimbabwe and Botswana rely on coal

Table 4.1: *Installed capacity by source for each modelled country.*

"Hydro-advanced" stands for all the hydropower plants modelled implementing hydrological constraints, namely the ZRB plants. "Hydro-base" instead are for all the hydropower plants modelled in a traditional way.

Installed Capacity [MW]	South Africa	Zimbabwe	Zambia	Botswana	Mozambique	Namibia
Coal	37868	1190	300	732	-	120
Diesel Engine	-	-	89	70	-	39
Nuclear	1860	-	-	-	-	-
OCGT	3409	-	-	90	38	-
Gas Engine	-	-	-	-	500	-
Solar PV	1474	-	1	-	-	-
Wind	2078	-		-	-	-
Hydro-base	600	-	208	-	17	300
Hydro-advanced	-	750	2190	-	2075	-
HFO	-		110	-	-	-
Biomass	-	97		-	-	-

[2]Data source: https://www.iea.org/data-and-statistics/data-tables?country=CONGOREP&energy=Electricity&year=2017

[3]Data source: *Eskom* (2018), *ERB* (2018),*Climate scope* (2015), *Namibia Power* (2020),*BPC* (2017),*EDM, Electricidade de Mozambique* (2020), *The Republic of Mozambique Ministry of Mineral Resources and Energy* (2018). Values reported may differ looking at different reports.

too. On the contrary, all the other SAPP members are characterized by a predominant hydroelectric production with a little percentage of fossil fuel power plants.

Concerning renewable technologies, they are characterised by a variable power production which has to be provided exogenously as a timeseries. For this task we extracted online[4] the historical timeseries for PV and wind power plants for a specific location exploiting global database like MERRA-2[5]. The timeseries are referred to specific coordinates, but since we described each country as a network point, we chose a reference position looking at the distribution of existing plants.

4.3.2 Energy demand

The hourly timeseries of energy demand is the most difficult data to retrieve. Unfortunately, hourly power demand timeseries are not always available for each country. As a consequence we built hourly demand profiles exploiting available data from local authorities energy reports.

For Mozambique, Namibia, Zambia and South Africa we found different load curves representative of different typical days of the years[6] (e.g. winter and summer days or weekday and weekend day). An example of load curve is shown in fig.4.5 for the case of Namibia. Then these profiles have been scaled along the year accordingly to data available (e.g. weekly mean, monthly or

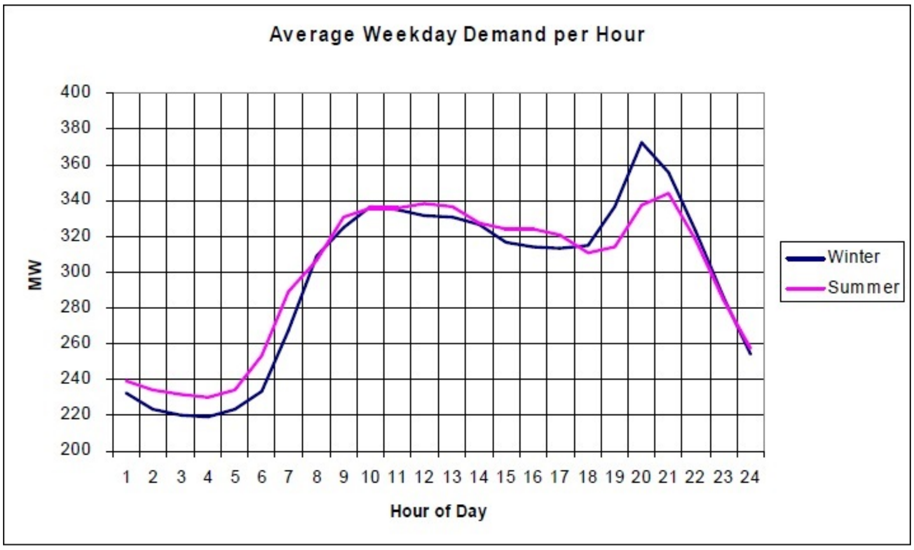


Figure 4.5: *Namibia power load curve (source: EMCON Consulting Group (2006)).*

[4]`https://www.renewables.ninja/`
[5]`https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/`
[6]Data source: *EDM* (2015), *EMCON Consulting Group* (2006), *Ministry of Energy and Water Development* (2010), *Urban Energy Support* (2015)

seasonal energy consumption). Where load curves were not available (i.e. Zimbabwe and Botswana), we built demand profiles referring to neighbours countries and scaling properly on the basis of national average energy consumption[7].

4.3.3 Transmissions

Modelling transmissions is crucial to understand the energy interconnection between countries and also to analyse the benefit of future energy grid expansion. Fig.4.6 shows existing transmission lines, their working voltage and energy capacity. Since the network scheme was built at national scale, we only account for trasmission lines without modelling the distribution lines installed in the countries. Since the real electric system is characterised by high energy losses related to the distribution, further developments should take into account such losses.

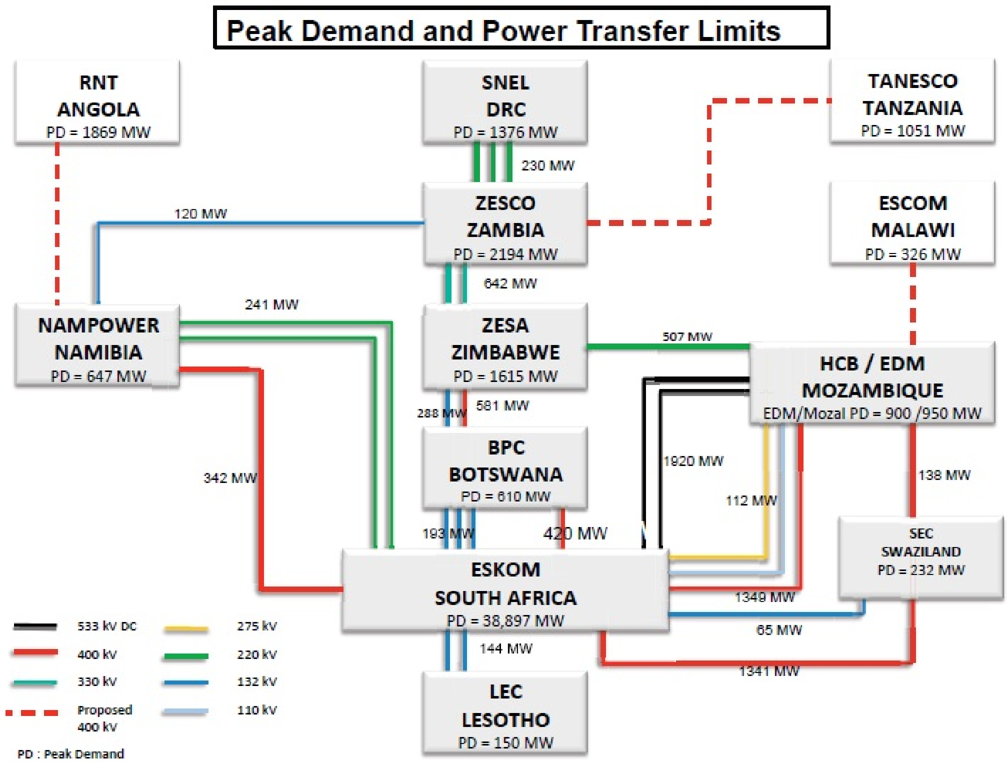


Figure 4.6: *SAPP electric transmission (source: SAPP (2018)).*

[7]Data source: *ZERA* (2017), *BPC* (2017)

4.4 Modelling the ZRB

The improved modelling of hydropower generation introduced in section 3.3.1 is implemented for the four main dams of the Zambesi River Basin: Itezhi-Tezhi ("ITT", 120 MW), Kafue Gorge ("KGU", 990 MW), Kariba ("KA", 1.8 GW) and Cahora Bassa ("CB", 2 GW). The complete modelling configuration is represented in fig.4.7. It is important to remember that for every arrow crossing

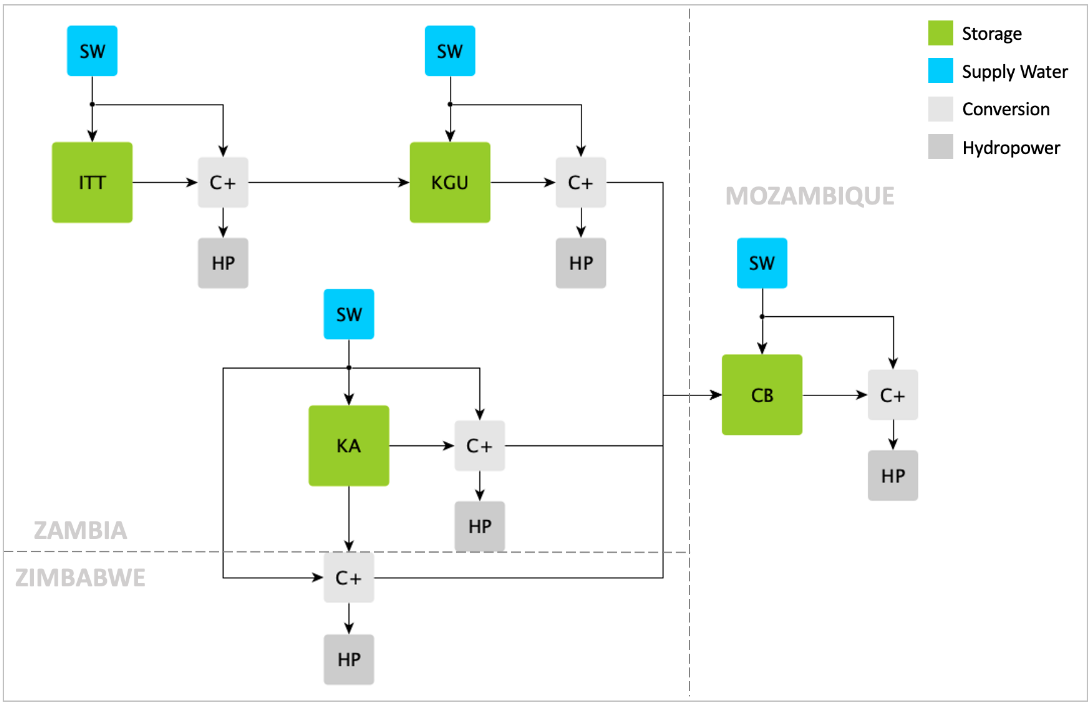


Figure 4.7: *ZRB configuration scheme in Calliope.*

national boundaries a *water transmission* technology is required, both to connect hydropower plants and reservoir of different countries (i.e. the case of Kariba plants straddling Zambia and Zimbabwe) and to allow water flowing from Zambian reservoirs to Cahora Bassa in Mozambique. Another reminder regards the spillage technology represented by a *conversion* technology named spillage for each reservoir (as described in section 3.3.1): for the sake of clarity we did not included it into the scheme.

Inflow timeseries are the input water resource provided by *supply_plus* technologies (SW); data come from the ADAPT project (*Matos et al.*, 2015). Regarding storage technology parameters, data about reservoirs operational constraints as maximum and minimum release (fig.4.8) come from *Gandolfi et al.* (1997), the Zambezi River Authority[8] and Hidroeléctrica de Cahora Bassa[9].

[8] http://www.zambezira.org
[9] https://www.hcb.co.mz

Storage initial and final values are extracted from dams operational rule curves (fig.4.8) (*Cervigni et al.*, 2015). In order to compute evaporation losses and variable hydraulic head in the external loop as discussed in section 3.3.2, evaporation rates are provided by *Beilfuss and dos Santos* (2001) while reservoirs level-storage and surface-storage curves (fig.4.9) are taken from *The World Bank* (2010).

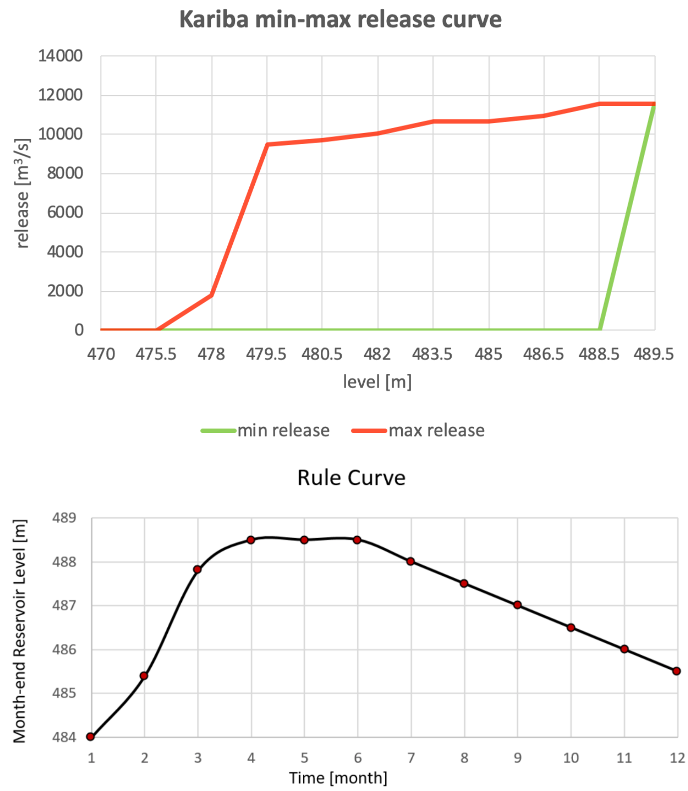


Figure 4.8: *Kariba minimum-maximum release and operational curves.*

4.5 Simulation settings

Our analysis is splitted into two phases: the first one aims at simulating the system under different hydrological scenarios, in the second one we validate our model with respect to observed data.
The simulation time-step of the model follows the hourly power demand profile. The time horizon should be set in order to capture the full hydrological dynamic of reservoirs under analysis. It means we should consider a period as long as the time to completely fill or empty reservoirs starting from the minimum or the maximum level respectively. In principle, for our case study we should have set a simulation horizon of at least 5 years, but the model would

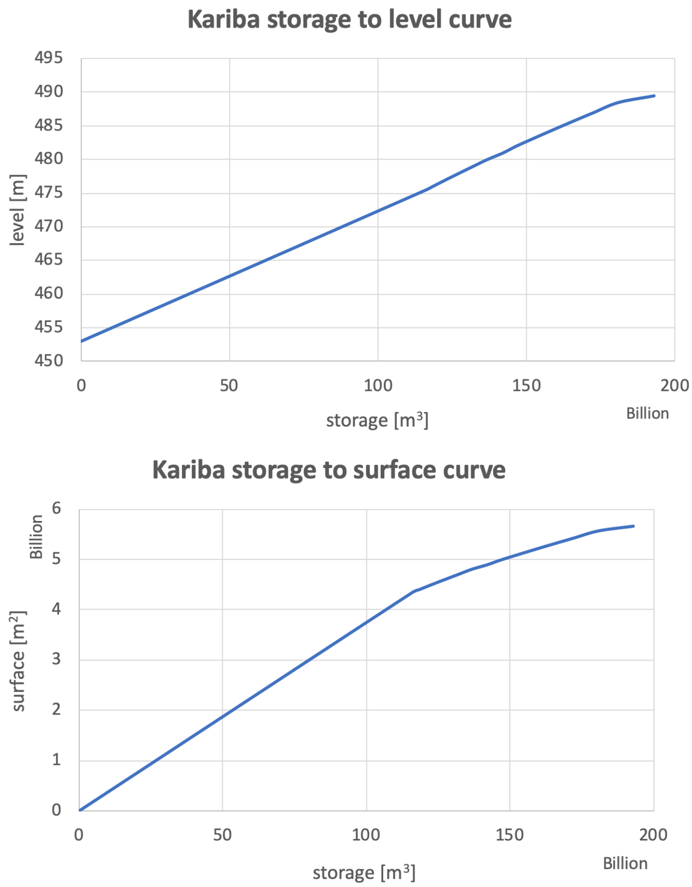


Figure 4.9: *Kariba level-storage and level-surface curves.*

not support such a computational effort for the system deterministic optimization. That's why we chose to limit the time horizon to 2 years while exploring hydrological variability thanks to different inflow scenarios. This approach wants to simulate the so-called "Monte Carlo analysis", which aims at evaluating the model with a set of random parameters as inputs. These parameters are generated from the probability functions of the variables, thus mimicking the sampling procedure of the phenomena under analysis. In our work, we exploited twenty years of historical inflow data (from 1986 to 2005) in order to run 10 different experiments exploring both inflow peaks and dry periods. Fig.4.10 shows cumulated inflow for each historical year and for each reservoir.

Beyond inflows, also varying the initial and final values of the reservoir storage may produce interesting results. In our case, we took as storage inputs the data from dams operational rule curves assuming them as the optimal ones. Simulations start the first day of January and end the last day of December. The reservoirs main parameters are summarized in table 4.2, in which the initial

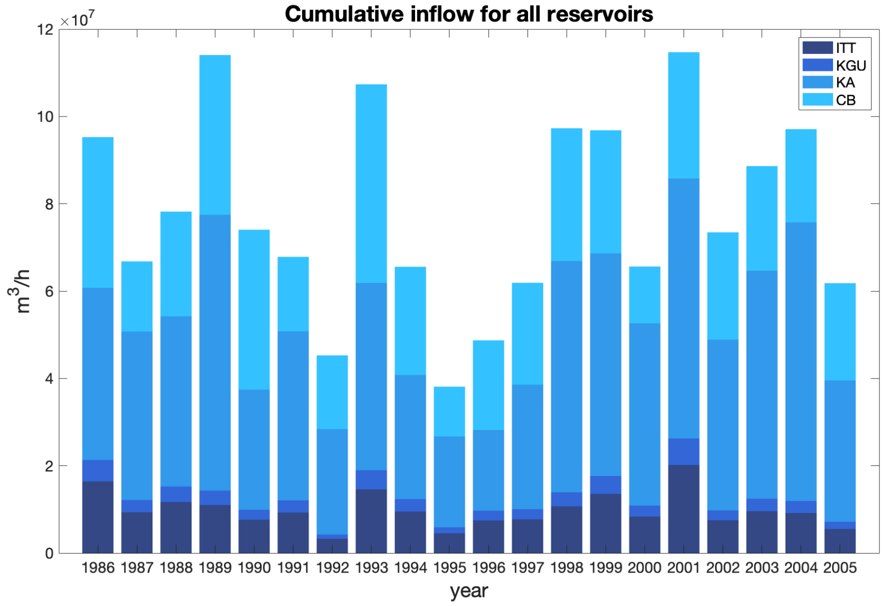


Figure 4.10: *Cumulated hystorical inflow from 1986 to 2005 for Zambesi River Basin reservoirs.*

Table 4.2: *ZRB reservoirs Calliope_hydro main parameters*

Parameters	Itezhi-Tezhi	Kafue Gorge	Kariba	Cahora
Live storage [m^3]	$5.18*10^9$	$1.18*10^9$	$6.47*10^{10}$	$5.17*10^{10}$
Hydropower capacity [MW]	120	990	1080	2075
Maximim turbines release [m^3/h]	612	252	2040	2260
Maximim hydraulic head [m]	40.5	397	110	128
Maximum storage level variation [m]	25	5	11	35
Initial storage [%]	0.6049	0.3257	0.7715	0.854

storage values are expressed as a percentage of the live storage capacity.
As explained in section 3.3.2, an iterative external loop is used in our model to evaluate evaporation losses and time varying hydraulic heads. For each simulation, 20 iterations are run and the convergence of the procedure is verified as discussed in the next chapter.

Simulations are performed without setting any constraint on technologies production, meaning that we are not imposing a minimum rate of production for fossil fuel technologies. We let the model optimize the overall system from an economical point of view; for this reason we do not expect results to mirror the actual SAPP production because they will represent the optimal grid operation. Since the model is run with perfect foresight, has the possibility of exploring solutions with higher share of renewable generation abandoning energy production from coal. This motivated a further modification of the model with the goal of better reproducing the observed operation of the system in a specific year. For this simulation, only existing technologies at that time will be modelled and a rate of minimum production for coal based plants will be imposed. The capacity factor C_f is computed as follow:

$$C_f = \frac{E_{prod}\,[GWh]}{E_{TOT}\,[GWh]} \tag{4.1}$$

where E_{prod} is the yearly energy produced by coal[10] and E_{TOT} is the total amount of energy which could be produced by coal technologies, i.e. the installed capacity multiplied by the hours in a year. In order to replicate the real system behavior, we will set also historical initial and final storage values of ZRB reservoirs (where available[11]). In this way we allow the model to produce an increase/decrease of storage over the 12 months of simulation.
The analysis of the results will be discussed comparing the advanced hydropower modelling (*Calliope_hydro*) with the equivalent standard version (*Calliope_base*), where hydropower is modelled only providing installed capacity (as explained in sec.3.2). Simulations settings for each experiment are summarized in tab.4.3.

Table 4.3: *Simulations settings for all the experiments considered.*

Settings	*Calliope_base* simulation	*Calliope_hydro* simulations											
	s0	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10	sC1	sC2
Time horizon (years)	2	2	2	2	2	2	2	2	2	2	2	1	1
Advanced hydropower modelling	✘	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Inflow pattern	✘	1986-87	1988-89	1990-91	1992-93	1994-95	1996-97	1998-99	2000-01	2002-03	2004-05	1998	2005
Additional constraints	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	✘	coal capacity factor	coal capacity factor

[10] Data source: `https://www.iea.org/data-and-statistics`
[11] Data source: *Ministry of Energy and Water Development* (2010), *Beilfuss and dos Santos* (2001)

5

Results

In section 4.5 we talked about the rational followed in order to show the benefit of integrated modelling of hydropower. The analysis can be splitted into two phases. In the first one, we compare the behavior of the water-energy model (*Calliope_hydro*) with the traditional version one (*Calliope_base*), analysing results variability related to different hydrological scenarios. In the second phase, we discuss results obtained adopting models configurations which improve *Calliope_hydro* in order to respect the realistic operation of coal-based plants. This will be done from a comparative point of view with observed energy data validating *Calliope_hydro* results.

5.1 *Calliope_base* vs *Calliope_hydro*

In order to test the improved version of *Calliope_base* (i.e. *Calliope_hydro*), we simulated 10 different hydrological scenarios derived from the historical time-series of inflow of the main reservoirs in the Zambezi River Basin. In particular, the results presented in this section refer to a single simulation performed over the 1996-1997 inflow scenario and focus on the hydropower production in the ZRB. In this period inflow are not particularly abundant (see fig.4.10) and spillage technology is never activated by the model. An extensive analysis of the role of hydrologic variability using the other hydrologic scenarios is then reported in the next section.
In fig.5.1, 5.2, fig.5.3 and 5.4 the domestic power production of respectively Zambia (ZA), Zimbabwe (ZW), Botswana (BO) and Mozambique North Cen-

ter (MZn) is reported, for *Calliope_base* (on the left) and *Calliope_hydro* (on the right). *Calliope_hydro* results show the different contribution of the ZRB hydropower plants: Itezhi-Tezhi (ITT), Kafue Gorge Upper (KGU), Kariba (KA) and Cahora Bassa (CB). *Calliope_hydro* allocates hydropower production according to water availability, while *Calliope_base* lets hydropower produce at its nominal capacity every time of the year. This simplistic strategy yields to an unrealistic dispatchability of energy production, risking to overestimate hydropower generation especially in dry periods.
This limitation of *Calliope_base* is particularly highlighted by the results obtained for Zambia and Zimbabwe power productions, where hydropower is largely overestimated. In Zambia it exceeds power demand and the 29% of total production is exported to Zimbabwe, which similarly satisfies most of its energy requirements thanks to hydropower production. Hydroelectric in Zimbabwe covers 82% of its demand in *Calliope_base* while in *Calliope_hydro* it is reduced to 27%. In *Calliope_base*, Zimbabwe is importing energy from Zambia to partially cover its internal demand and partially export it to Botswana; this happens because there is not a direct transmission line connecting Zambia and Botswana. In detail, more than the 31% of the energy flowing in the Zimbabwe grid is exported to Botswana. Instead in *Calliope_hydro* Zambia is not exporting and needs to cover its energy demand with 11% of coal-based generation. As a consequence, Zimbabwe needs to import energy from Mozambique North,

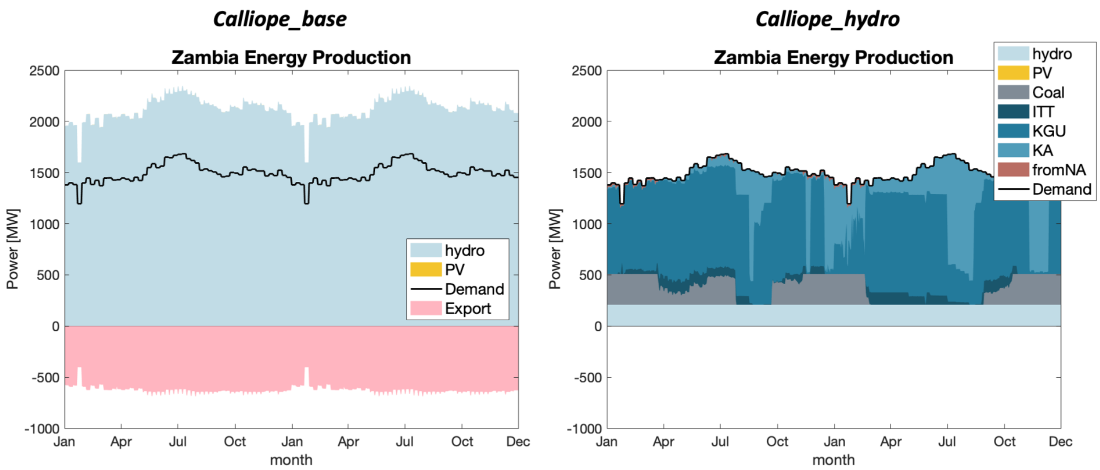


Figure 5.1: *Zambia energy production comparison between Calliope_base and Calliope_hydro.*

Even if simulation is performed with hourly time-step, results are plotted by daily average in order to facilitate representation. The entry "hydro" in the legend indicates all the hydropower plants modelled in a traditional way. Every entry in the legend actually contributes to power production; if it is not visible in the graph it is because of its extremely low generation share. Entries starting with "from" indicates energy imports from the related country (e.g. "fromNA" stands for energy import from Namibia).

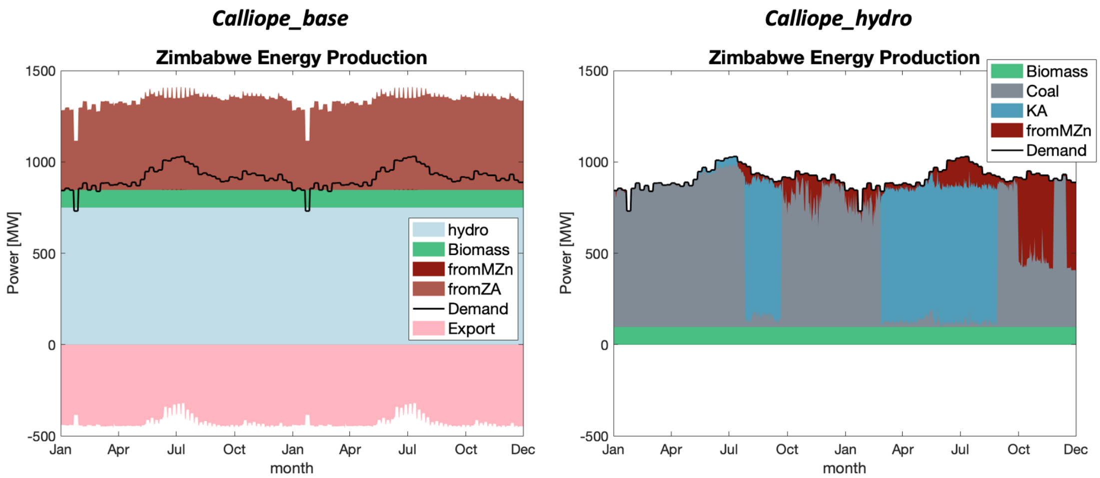


Figure 5.2: *Zimbabwe energy production comparison between Calliope_base and Calliope_hydro.*

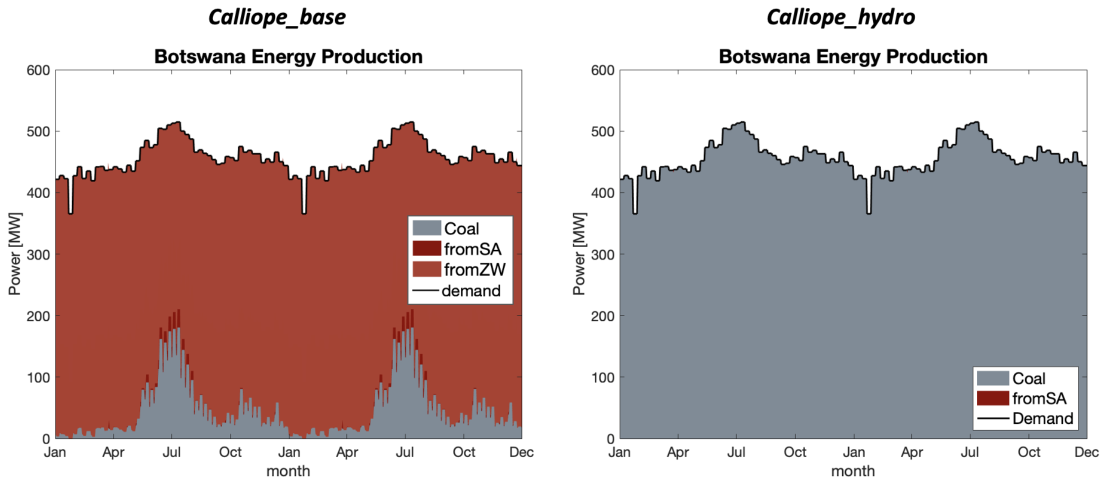


Figure 5.3: *Botswana energy production comparison between Calliope_base and Calliope_hydro.*

namely from Cahora Bassa hydropower plant, suspending export. Lastly, in *Calliope_hydro* Botswana has to satisify its power demand through a 100% coal-based generation, while in *Calliope_base* it imports 89% of clean hydropower energy.

The possibility of differentiating hydroelectric plants contribution in power generation allow us to investigate how *Calliope_hydro* is exploiting water resource in each reservoir. If we take as an example Kariba, we can notice the different distribution of the energy produced from this reservoirs among Zambia and Zimbabwe, where Kariba contribution is 27% of total. In Zambia, Kariba contributes for 17% of the total power production, while Kafue Gorge for 53% and Itezhi-tezhi for 4% (fig.5.5).

Concerning Cahora Bassa in Mozambique, it usually produces at its nominal capacity thanks to its configuration and location, largely exceeding Mozam-

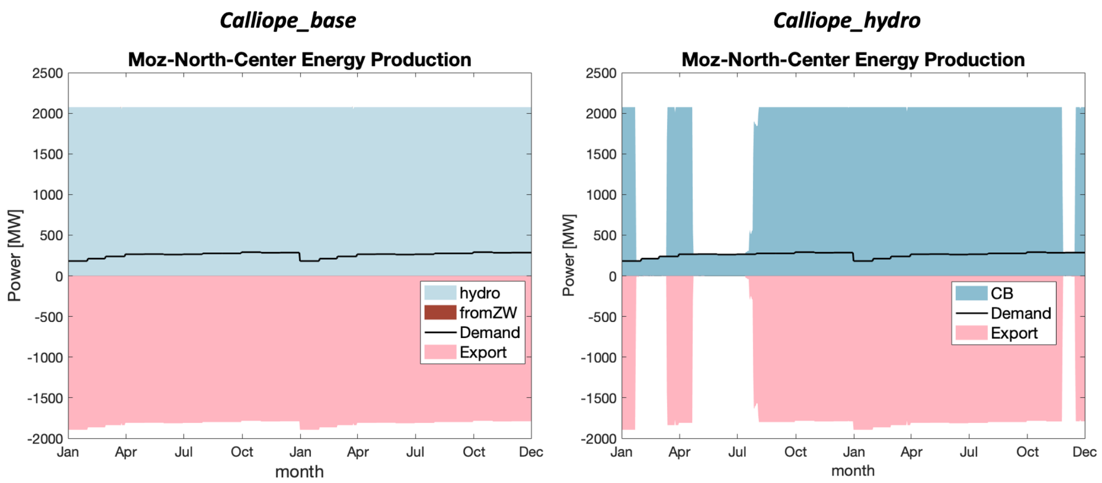


Figure 5.4: *Mozambique North-Center energy production comparison between Calliope_base and Calliope_hydro.*

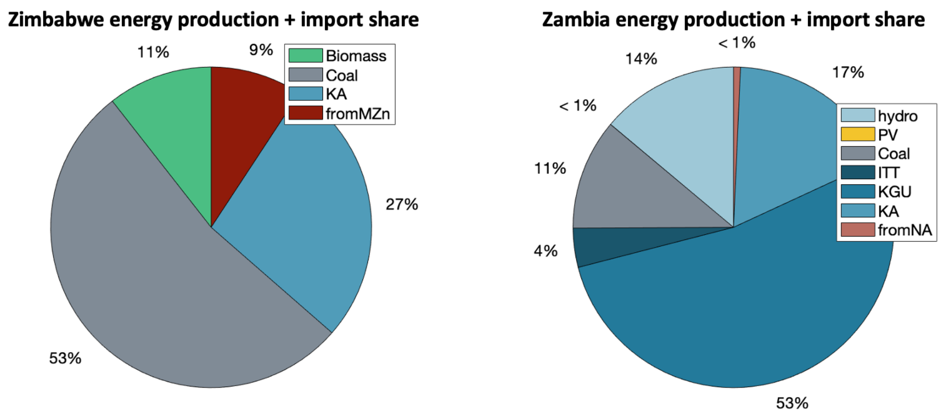


Figure 5.5: *Calliope_hydro energy production shares in Zambia and Zimbabwe.*

bique North power demand. Cahora Bassa is the last reservoir of the cascade configuration; in addition to its inflow, it takes as input all the releases of upstream reservoirs. That's why it is less influenced by dry season and its hydropower installed capacity is the highest of the ZRB plants. Differences between models can be appreciate in terms of suspendend hydropower overproduction as export to South Africa, whose generation mix is not influenced by hydrological constraints integration except for suspendend import from Mozambique North (fig.5.6).
Given the promising results obtained over a single inflow scenario, in the next section we discuss in details how the model responds to the variability of different hydrological scenarios.

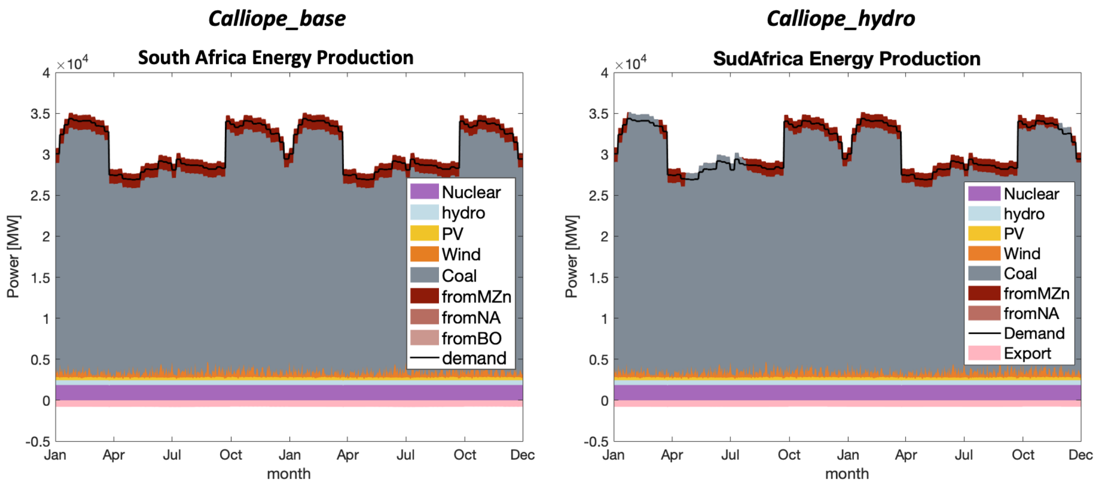


Figure 5.6: *South Africa energy production comparison between Calliope_base and Calliope_hydro.*

5.2 Hydrological scenarios

In this section we explore *Calliope_hydro* behavior under different hydrological scenarios by exploiting 20 years of historical inflows for the ZRB reservoirs. Since our simulation time horizon is 2 years, we have 10 different scenarios explorable. In addition, this modelling strategy allows investigating the impacts for the model to cope with diverse hydrological conditions, including very wet and very dry scenarios.

In particular, we compare our reference scenario (1996-1997) which is one of the driest in the available dataset with the inflow observations over the period of 1988-1989, which, on the contrary, is among the wettest scenarios. Focusing on the results obtained for Zimbabwe (fig.5.7), we can notice the large differences in power generation comparing a dry and a wet scenario. In wet years, the energy system regulation changes and hydropower production become the main source of electricity covering almost all the demand. While energy generation from coal in the reference scenario cover more than half of the total production, it almost disappears in the wet scenario.

Analogue considerations can be done for the case of Zambia (fig.5.8). In wet years, generation from coal is completely replaced by 100% hydropower energy production. Water resource availability and associated hydropower potential exceeds Zambia power needs, enabling export to Zimbabwe, which in turn exports to Botswana (as also observed in the previous section). Furthermore, it is interesting to see how the production is allocated among the three different Zambian reservoirs and how hydropower production is allocated in different countries. For the case of Kariba reservoir, which provides water and electricity to two different power plants, one located in Zambia and one in Zimbabwe. It is

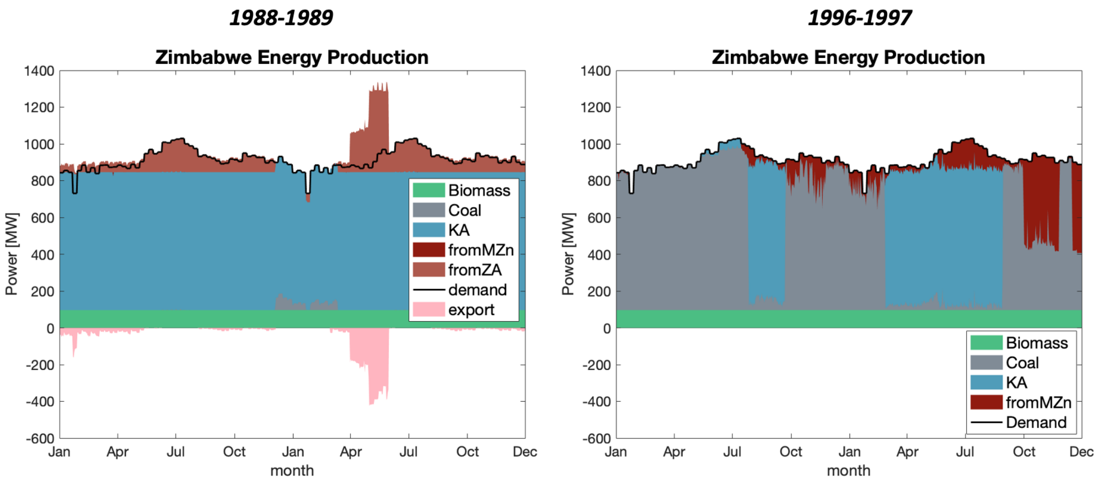


Figure 5.7: *Zimbabwe energy production comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

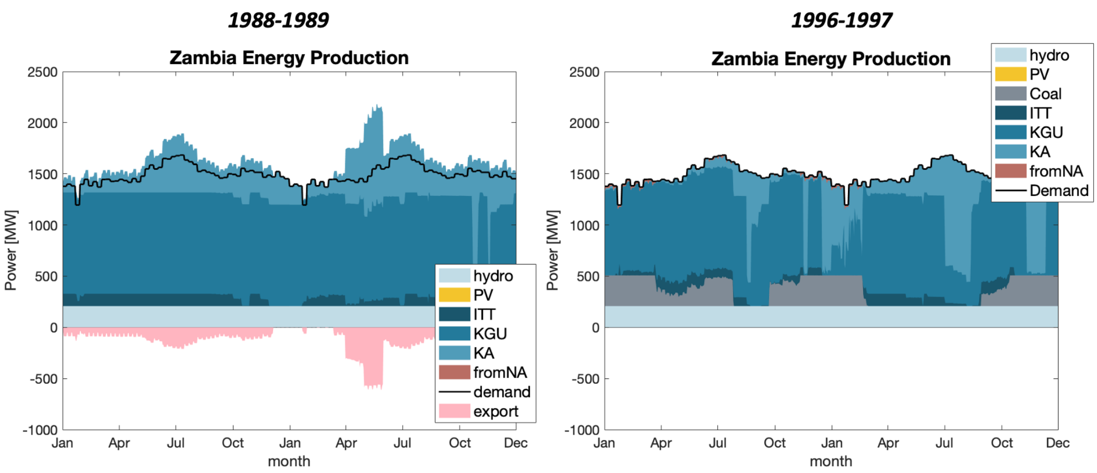


Figure 5.8: *Zambia energy production comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

important to state here that we didn't modelled any contractual obligation between power producers as, for simplicity, we are focusing on a pure economic energy system optimization without accounting for political agreements.
Considering results obtained for all hydrological scenarios, Zimbabwe is one of the countries in which the variation of the energy mix among scenarios is much more evident (see tab.5.1). Kariba hydropower production goes from 16% to more than 82% of Zimbabwe energy demand, with a coal-based generation respectively of 69% and 0.01%. Zambia power production (tab.5.2) relies mainly on hydropower for most of scenarios, with a maximum coal share of 12.1%. High variability can be seen in hydropower production contribution of each reservoir, especially for Kafue Gorge (with a share in the range of 43.7% and 64.8%) and Kariba (with a production share between 14.7% and 32.2%). On

the contrary, Mozambique generation mix is not influenced by dry or wet seasons. As we already discussed, Cahora Bassa is the less sensitive reservoir to water availability, it always totally covers Mozambique power demand exporting most of its energy to South Africa. Finally, water availability influences also countries in which the advanced modelling of hydropower is not present. The most notable example is the case of Botswana (tab.5.3), which usually relies on coal, while in particular wet years it covers up to 13% of the energy demand by importing hydropower from Zimbabwe.

Table 5.1: *Zimbabwe energy mix among all hydrological scenarios.*

Technology	Zimbabwe energy mix among scenarios									
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Biomass	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%	10.6%
Coal	17.3%	0.7%	36.6%	36.7%	69.0%	53.0%	0.01%	0.01%	14.0%	28.9%
KA	68.7%	81.6%	49.7%	48.9%	16.0%	27.2%	82.1%	82.0%	73.2%	57.2%
Import from MZn	3.0%	0.0%	3.1%	3.4%	4.2%	9.3%	0.001%	0.04%	2.2%	0.8%
Import from ZA	0.5%	7.1%	0%	0.4%	0.3%	0%	7.3%	7.3%	0%	2.53%
DEMAND [MWh]	666667	666667	666667	666667	666667	666667	666667	666667	666667	666667
PRODUCTION [MWh]	643835	619178	646123	641038	637088	604986	618011	617496	651703	644477
IMPORT [MWh]	22850	72496	20544	27440	29579	61680	94838	75757	14963	57949
EXPORT	0.003%	3.6%	0%	0.3%	0%	0%	6.5%	3.8%	0%	5.1%

Table 5.2: *Zambia energy mix among all hydrological scenarios.*

Technology	Zambia energy mix among scenarios									
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
hydro	13.9%	12.8%	13.9%	13.9%	13.9%	13.9%	12.5%	12.7%	13.9%	13.2%
PV	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%
Coal	0.7%	0%	5.1%	6.7%	12.1%	11.2%	0%	0%	0.9%	4.0%
ITT	6.0%	5.1%	4.3%	4.0%	3.7%	3.9%	5.3%	5.2%	4.3%	3.7%
KGU	64.8%	60.1%	58.7%	57.0%	43.7%	52.9%	59.5%	61.0%	59.6%	46.9%
KA	14.7%	22.0%	17.8%	18.5%	26.0%	17.4%	22.8%	21.2%	21.3%	32.2%
Import from NA	0%	0%	0.2%	0.01%	0.6%	0.7%	0%	0%	0%	0%
DEMAND [MWh]	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008	1090008
PRODUCTION [MWh]	1093447	1181945	1088193	1089920	1083908	1082633	1212353	1185093	1090152	1144329
IMPORT [MWh]	339	5	2116	4819	8103	7604	0	5	360	2620
EXPORT	0.35%	7.8%	0.03%	0.4%	0.2%	0.02%	10.1%	8.0%	0.05%	5.0%

Table 5.3: *Botswana energy mix among all hydrological scenarios.*

Technology	Botswana energy mix among scenarios									
	s1	s2	s3	s4	s5	s6	s7	s8	s9	s10
Coal	100.0%	92.9%	100.0%	99.5%	100.0%	100.0%	86.8%	92.4%	100.0%	89.8%
Import from SA	0.003%	0.01%	0.003%	0.01%	0.003%	0.003%	0.01%	0.01%	0.003%	0.03%
Import from ZW	0.01%	7.1%	0%	0.5%	0%	0%	13.2%	7.6%	0%	10.19%
DEMAND [MWh]	333333	333333	333333	333333	333333	333333	333333	333333	333333	333333
PRODUCTION [MWh]	333307	309548	333324	331591	333324	333324	289460	308056	333324	299267
IMPORT [MWh]	27	23785	10	1742	10	10	43899	25280	10	34081
EXPORT	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

5.3 The spillage

The results of *Calliope_hydro* over different hydrologic scenarios highlight the role of the spillway technology we introduced in Calliope. This technology is not activated in dry years and therefore it does not influence the results in sec.5.1, but it becomes more important in wet scenarios. We remind that the spillage is defined as a *conversion* technology linking two cascade reservoirs with null efficiency in order to discourage its activation. This means that water allocated to this technology does not reach the downstream reservoir and "leaves" the system. Given this limitation of our model, in this section we aim at quantifying the impacts of this imperfect implementation of the spillway. Since spillways are activated especially in wet conditions, we initially focus on the inflow scenarios of 1988-1989 and 2000-2001, which are two very wet scenarios.

The results in fig.5.9 illustrate the model outputs for Kafue Gorge as the small capacity of this reservoir is expected to make this hydropower plant the most sensitive to the spillway activation. We see in blue the water spilled compared with the natural inflow entering the reservoir for the two considered inflow scenarios. It is clear that Kafue Gorge spills especially in correspondence of high inflow. This is coherent with its small capacity with respect to the other ZRB reservoirs, meaning that it tends to fill up quickly.

Concerning Itezhi-Tezhi, the spillage is less impacting as illustrated in fig.5.10. The spillage technology is activated less frequently and for shorter period with respect to KGU; in this case spillway disappears in inflow scenario of 1988-1989, while it appears in a short period of 2000-2001 scenario in correspondence of inflow peak. Thanks to the bigger storage capacity than the one of Kafue Gorge, Ithezi-thezi reservoir is able to better manage inflow peaks and water excess,

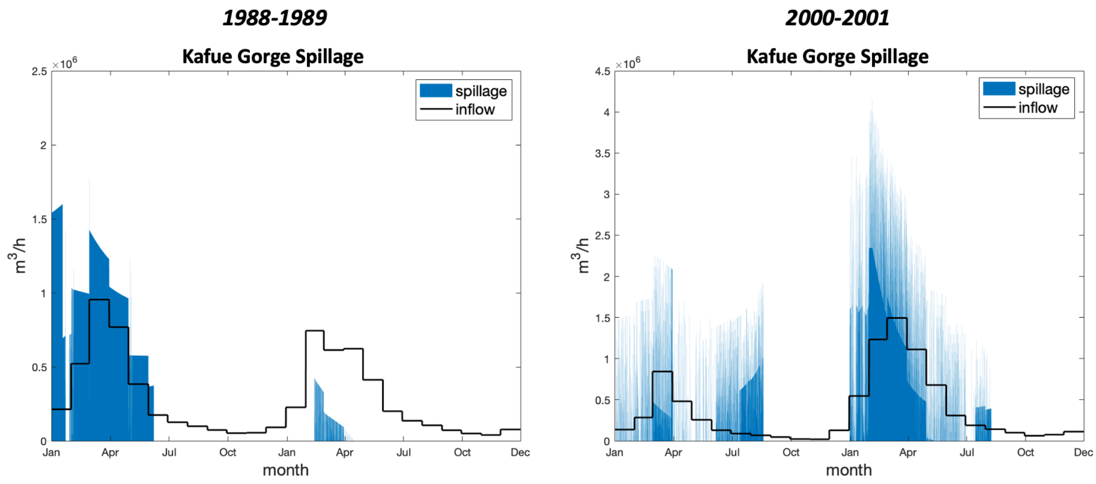


Figure 5.9: *Kafue Gorge spillage in Calliope_hydro scenarios of 1988-1989 and 2000-2001.*

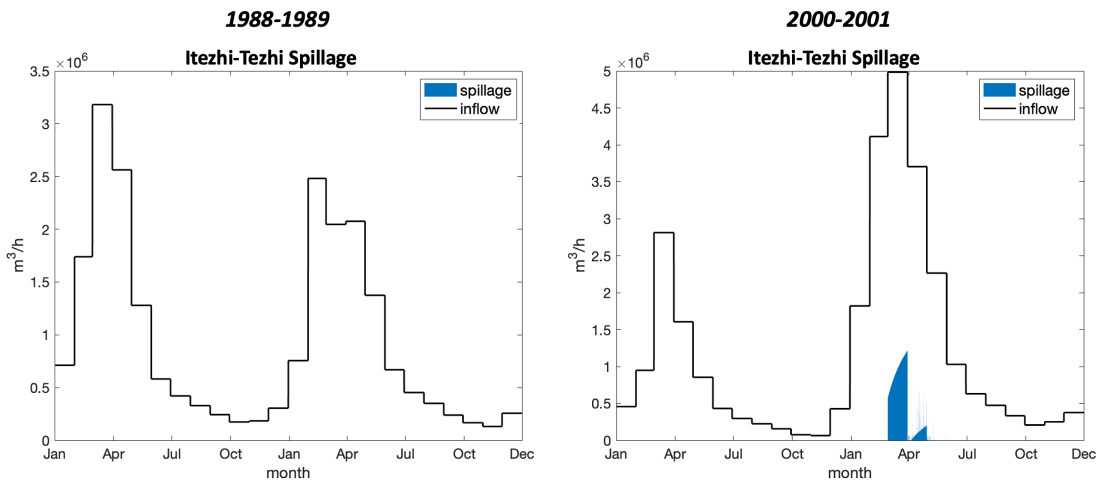


Figure 5.10: *Itezhi-Tezhi spillage in Calliope_hydro scenarios of 1988-1989 and 2000-2001.*

ultimately reducing the amount of water assigned to spillways (and lost in our model implementation).
The results discussed so far suggest that the bigger the storage capacity, the lower and less frequent is the spillage. This is confirmed by results obtained for Kariba reservoir, which never activates the spillway for any scenarios. Different results are instead obtained for Cahora Bassa. Despite its large storage capacity, fig.5.11 shows how the use of spillway in Cahora Bassa is not negligible. All simulations start with the initial storage that, according to the rule curve, exceeds the 85% of its maximum capacity. Since we imposes that the final storage value at the end of the two years simulation horizon should be equal to the initial one, this high storage initialization can become critical in wet scenarios over which the maximum release capacity could not be enough to meet the final storage value imposed. As a consequence, the model activates

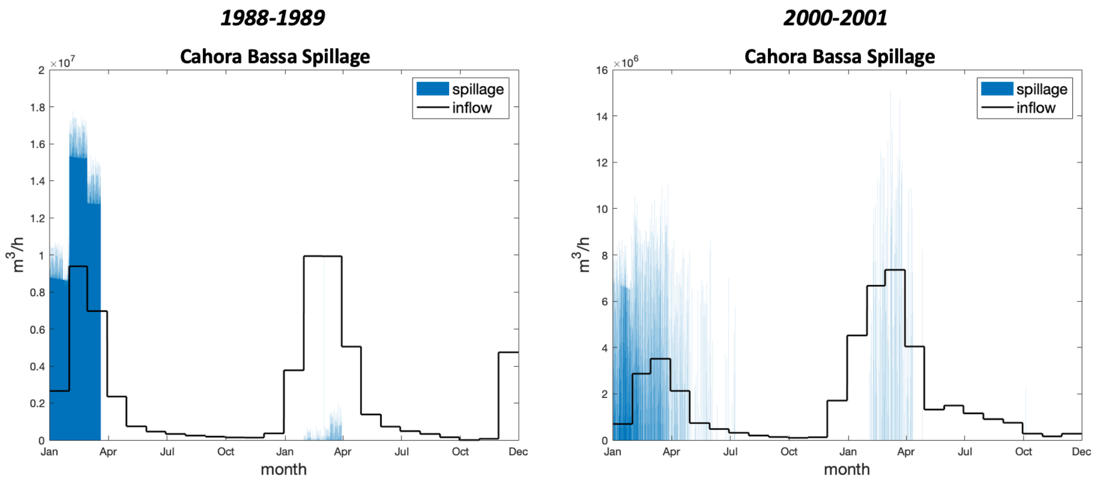
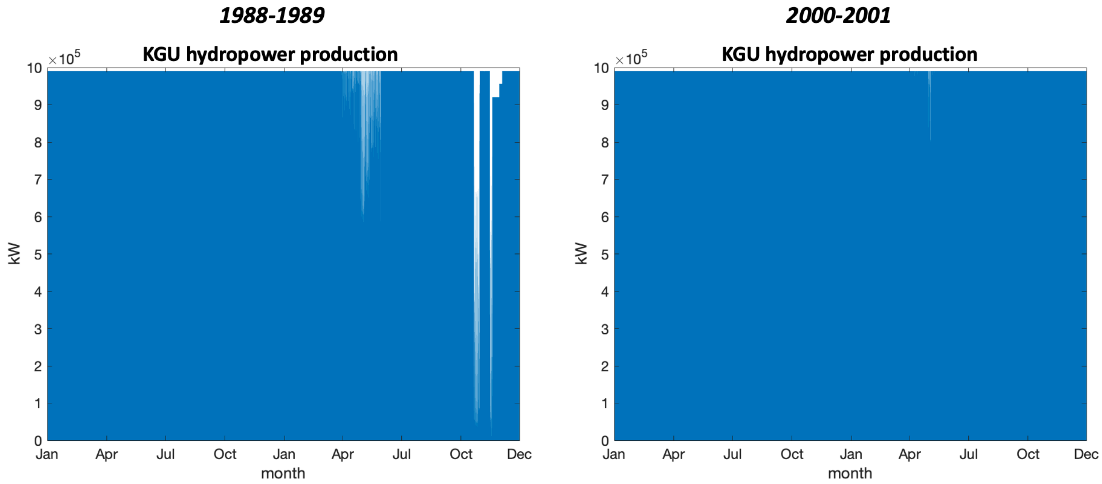


Figure 5.11: *Cahora Bassa spillage in Calliope_hydro scenarios of 1988-1989 and 2000-2001.*

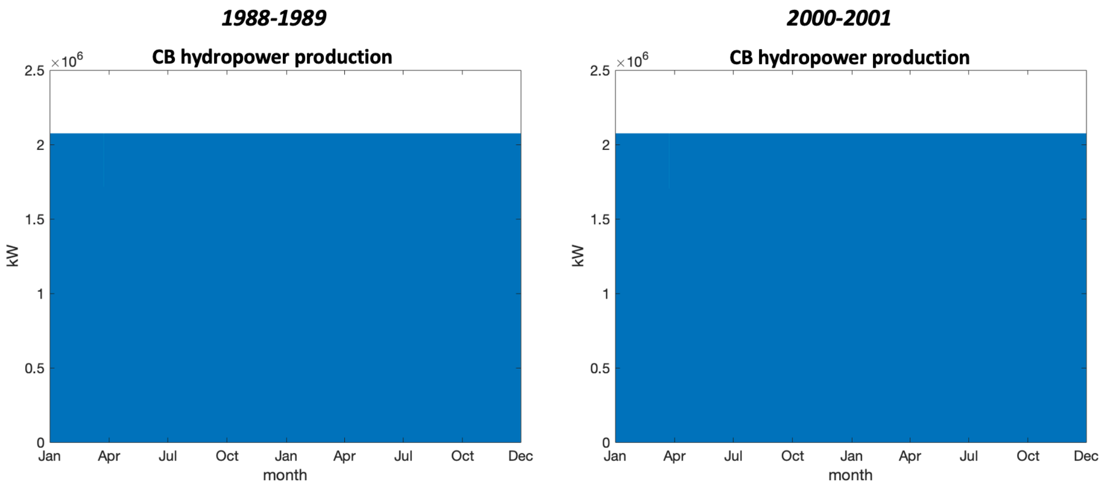
the spillway to drawdown the reservoir and meet the final storage constraint. Given this clear limitations, the first check we perform aims at verifying that when the spillway is active, the reservoir is also producing at maximum capacity by saturating the turbines. Results in fig.5.12 show that both Kafue Gorge and Cahora Bassa use their turbines at their maximum capacity during when the spillways are active. This suggest us that the water flow assigned to the spillage technology is effectively exceeding the maximum capacity of release. Now that we have clarified when and why *Calliope_hydro* activates the spillage technology, we want to quantify the error associated with this phenomenum. It is important to recall that the water spilled is a resource that is not flowing downstream but rather leaving the system, thus not contributing to the inflows entering Cahora Bassa. In order to quantify this error, we computed the ratio between the water spilled by Itezhi-Tezhi, Kafue Gorge and Kariba and the sum of all the streams that should enter Cahora Bassa, meaning the sum of its natural inflow and the releases from upstream reservoirs including the spillways. Results show that spillage technology is not activated for 3 scenarios out 10; the total amount of water spilled is in the range of 0.2% and 6.8% of the total resource ideally available at Cahora Bassa reservoir (tab.5.4), with an average error of 2.3% across all scenarios. This help us in identifying which could be the maximum error we are introducing by imperfect spillage modelling.

Table 5.4: *Error related to spillage technology activation across all hydrological scenarios.*

Error related to Spillage activation among scenarios									
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
5.7%	2.7%	0%	1.3%	1.8%	0%	3.5%	6.8%	0%	1.5%



(a) Kafue Gorge hydropower production.



(b) Cahora Bassa hydropower production.

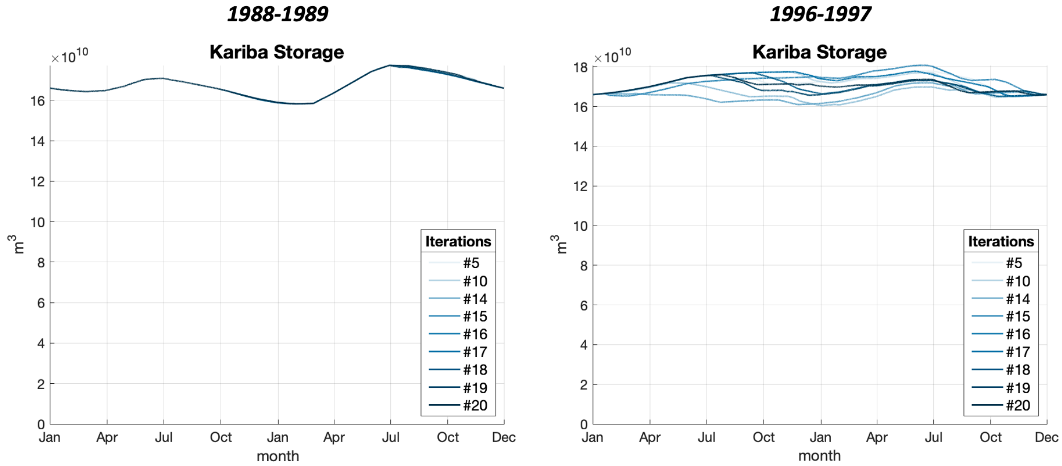
Figure 5.12: *Kafue Gorge and Cahora Bassa hydropower production in hydrological scenarios of 1988-1989 and 2000-2001.*

Cahora Bassa spillway has not been considered since it would flow outside our system boundaries (i.e. into the Indian Ocean) and it would affect the energy system only in case of unmet hydropower production due to water scarcity. As discussed before, actually Cahora Bassa plant produces at its maximum capacity in all the events when spillway is active, thus hydropower production is not influenced by missing water flow.
Finally, we can assert that the rough modelling of the spillage technology has a limited impact on *Calliope_hydro* results, without undermining the validity of our work. Looking ahead, future works should aim at a flawless spillage technology definition and implementation in order to achieve a fully integrated water-energy system modelling.

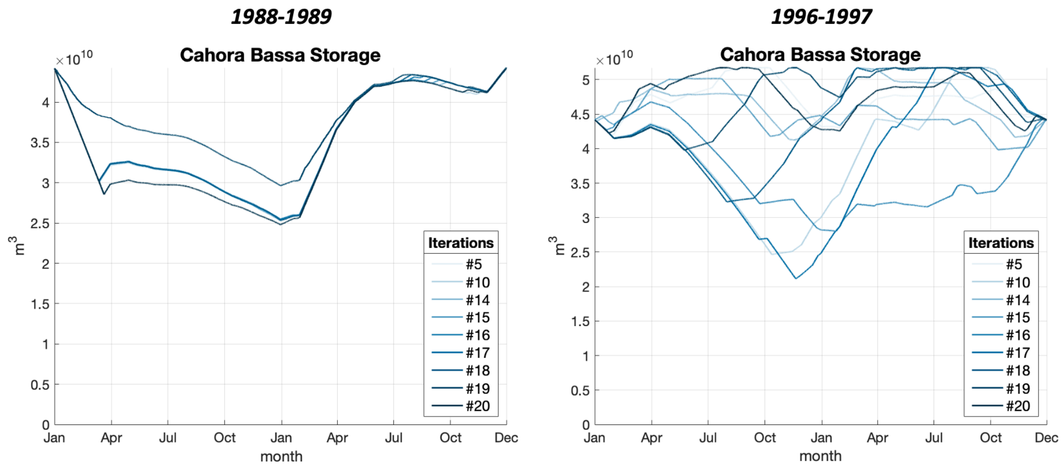
5.4 External loop convergence

Another feature of *Calliope_hydro* is the possibility of modeling evaporation losses and time varying hydraulic heads that are updated according to the dynamics of the reservoir storage by means of an external loop (see section 3.3.2). It is important to remind that the external loop should be iterated until convergence is reached. Given the high time-demanding simulations, we fixed the maximum number of iterations equal to 20; running 20 iterations require a simulation time of about 20 hours[1] with user's interaction. The convergence is then evaluated at the end of simulation as the difference between storage timeseries of the last two iterations.
In particular, in this section we compare two cases: a particularly wet scenario (1988-1989) and a dry one (1996-1997). Fig.5.13 shows storage trajectories of the two biggest ZRB reservoirs: Kariba and Cahora Bassa. Focusing on Kariba, we can see that convergence is perfectly reached after the first iteration for the inflows of 1988-1989, while in the dry scenario one some oscillations appear. Anyway, the amplitude of such fluctuations is of small entity and decreases with each new iteration, thus we can assert that Kariba storage timeseries almost converge after 20 iterations.
Different results are instead obtained in the case of Cahora Bassa. Considering the wet scenario 1988-1989, we can see that convergence is guaranteed for the first eighteen iterations, then iteration #19 differs from the others while the last one returns to approach convergence. This is because a small variation in the input data may lead *Calliope_hydro* to explore new solutions, very different from the previous ones but equally economically optimal. For this reason we can assert that iteration #19 is an isolated deviation and Cahora Bassa storage timeseries convergence will be probably reached again after few additional iterations.
On the contrary, this does not happen for the dry scenario (1996-1997), suggesting that the lower availability of water relax storage management constraints, letting the model more freedom for water resource allocation. Given the large capacity of Cahora Bassa reservoir, it is clear that the model has countless number of possible solution for managing the scarce water available, especially in dry periods, but all equally economically optimal. Contrariwise, under wet scenarios the model has less freedom of allocating water resource, because high cumulated inflow or seasonal peaks represent a strong constraint for water storage management. The need of manage a high water inflow added to the hydrological constraints modelled forces the model to an almost univocal behavior.

[1]Simulation time estimated referring to Intel Core i7 processor, RAM 8 GB.



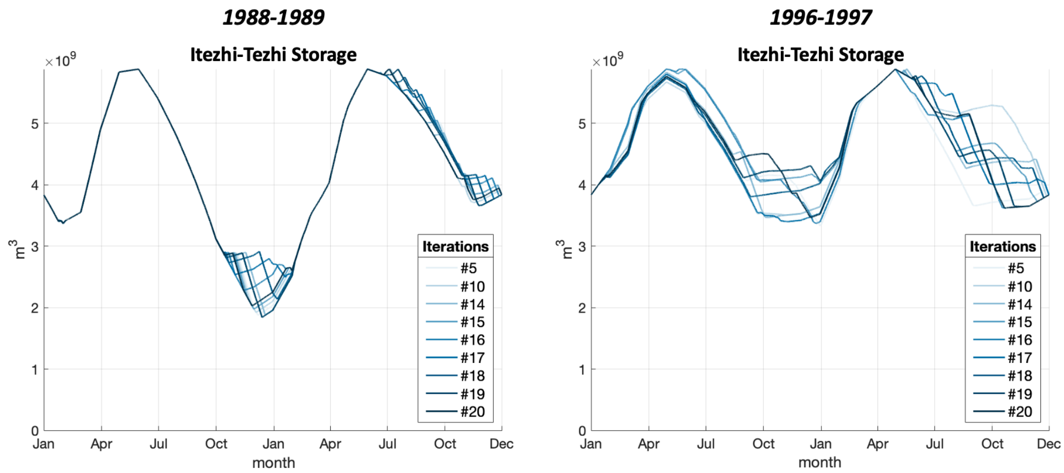
(a) Kariba storage trajectories comparison.



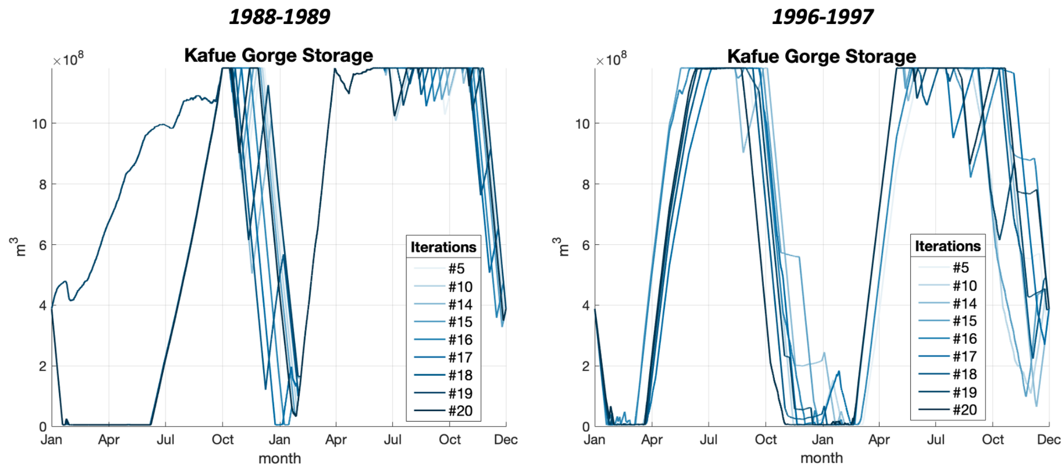
(b) Cahora Bassa storage trajectories comparison.

Figure 5.13: *Kariba and Cahora Bassa storage comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

This hypothesis is confirmed by fig.5.14, where the storage trajectories of the two smaller reservoirs, Itezhi-Tezhi and Kafue Gorge Upper, are illustrated. For both reservoirs we can see that under wet conditions the storage timeseries fluctuations are narrowed and limited to two specific periods along the time horizon. For Kafue Gorge, we can see an isolated deviation from convergence in the first year of the time horizon for iteration #19; anyway, iteration #20 overlaps again the converged trajectory. On the other hand, similarly to what we observed previously, fluctuations' amplitude increases in the dry scenario. This result, which holds for all the reservoir, has been also verified in all the other simulations, thus suggesting a clear and consistent response of the model to the considered inflow scenario.
Beyond considerations about water availability and hydrological scenarios, Ka-



(a) Itezhi-Tezhi storage trajectories comparison.



(b) Kafue Gorge storage trajectories comparison.

Figure 5.14: *Itezhi-Tezhi and Kafue Gorge storage comparison between hydrological scenarios of 1988-1989 and 1996-1997.*

fue Gorge needs further analysis. The maximum variation of the water storage level is almost negligible compared to the maximum hydraulic head (see tab.4.2). As a consequence, the conversion efficiency timeseries dependent on time-variable hydraulic head does not affect how the model allocates water resource. This explain the large variability among iterations also for wet scenarios.
Results obtained so far show that 20 iterations are not always enough and achieving convergence is an open issue of our work, especially in dry periods. Taking as reference the hydrological scenario of 1996-1997, we performed 30 iterations in order to evaluate if convergence is improved. Storage timeseries trajectories continue to oscillate showing that convergence is not still reached even by increasing the number of iterations. This result allows us to assert that

Calliope_hydro is slightly sensitive to external loop constraints and under dry scenarios it does not reach an univocal optimum operation solution.
Now it is essential to understand if the convergence issue is undermining the energy system optimization. Results in fig.5.15 illustrate Zambia power production timeseries and share over the simulation horizon 1996-1997 for iterations #19 and #20. We can notice that power production share over the simulation horizon is constant for Itezhi-Tezhi, Kafue Gorge and Kariba. What is slightly changing is the different allocation of hydropower production over time. Anyway, the trend of hydroelectric generation is almost preserved, with similar periods of suspended production.

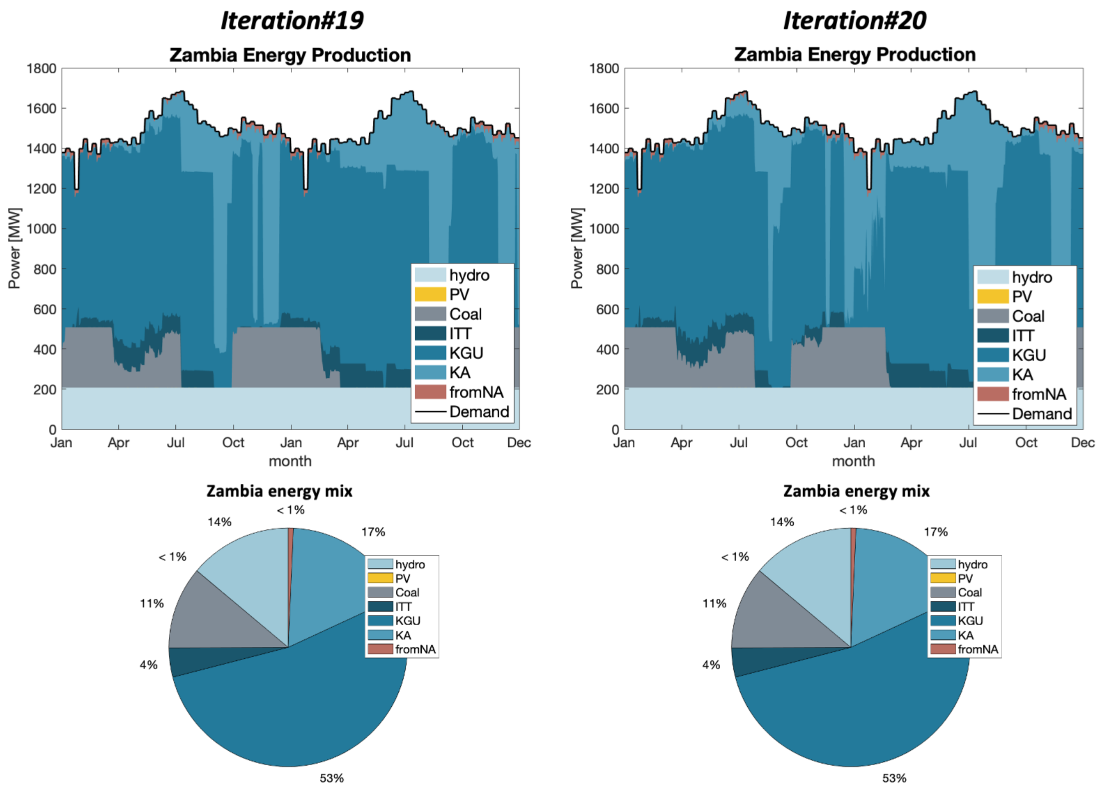


Figure 5.15: *Calliope_hydro power production in Zambia: comparison of iterations #19 and #20 of hydrological scenario 1996-1997.*

In order to weight computational effort and convergence accuracy, we also compare Zambia power production of iterations #29 and #30 (fig.5.16). The same considerations made above are still valid: the optimal energy mix has not changed and hydropower allocation over time is not still perfectly overlapped. Considering the overall trend among all the iterations, it is important to highlight that the optimal energy mix is reached after the first iteration, while the temporal allocation of hydropower production continue to oscillate without showing a convergence trend. For this reason, we can assert that the computa-

tional effort can be limited without affecting results accuracy.
We can conclude that, from an energy point of view, missing convergence does not affect the system optimization but the resource allocation over time. Further efforts have to be done in order to overcome the difference in storage timeseries for a more accurate and fully exhaustive hydrological description.

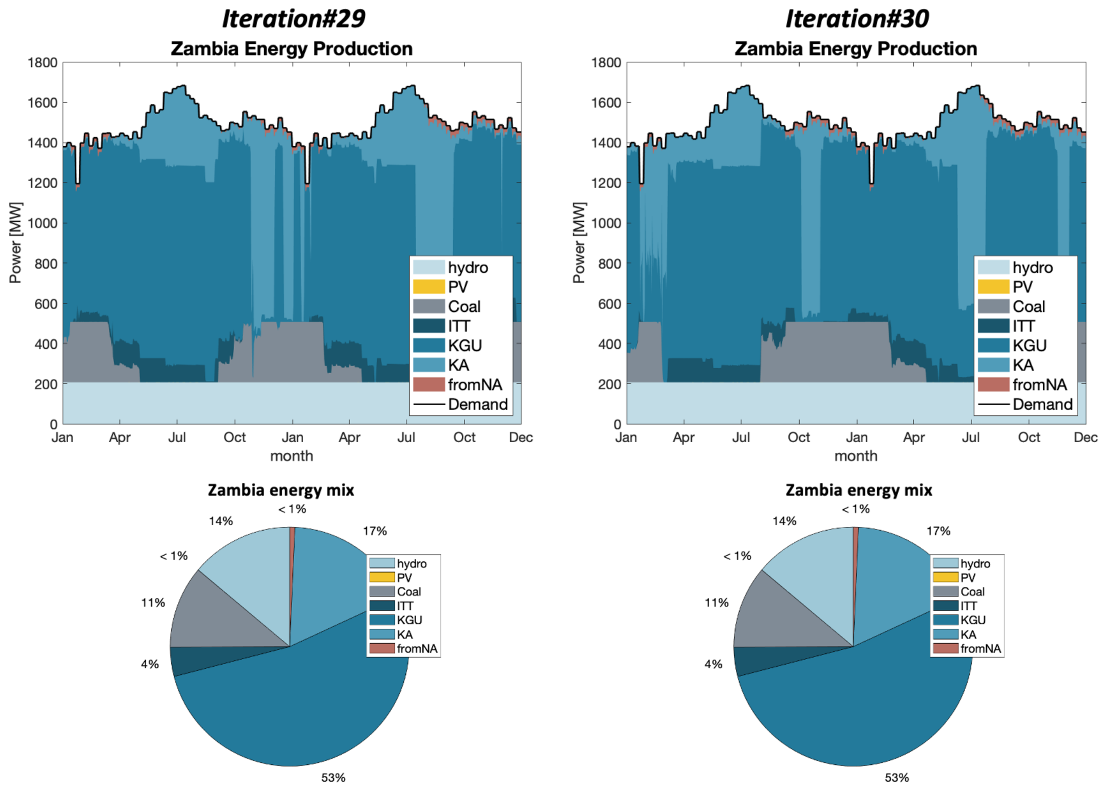


Figure 5.16: *Calliope_hydro power production in Zambia: comparison of iterations #29 and #30 of hydrological scenario 1996-1997.*

5.5 Simulating observed system behavior

Up to now, we analyzed the results of *Calliope_hydro* optimization under different hydrological scenarios, exploring also 100% renewable generation solutions. We observed that the variable generation of hydropower leads to an unrealistic usage of fossil fuel technologies, especially coal. For this reason, in this section we improve *Calliope_hydro* adopting models configurations which respect the realistic operation of coal-based plants and we validate our results comparing them to observed energy data.
In very wet scenario, coal is indeed used only in few periods of the year due to the high availability of water resources, conversely in real system operation coal plants are almost never turned off providing the energy baseload of most

countries. To mitigate this problem, we introduced a ramping rate by modelling the amount of time that a plant needs to reach its full power capacity. Despite this constraint, the new optimization still tends to switch on and off this technology, a challenge that old fossil fuel plants are facing in energy systems with an increasing share of renewable power characterized by variable energy production. In this changing context, fossil fuel technologies are forced to move from stable base load production to a more flexible one, covering the gap of renewable power generation. From an operational point of view, coal-based plant represents one of the less flexible technology in a real energy system and requires a constant power production along all the year.
To simulate the behavior of the real energy system, we therefore need some additional modelling settings. We select a specific year for simulation, we impose a minimum energy production for coal power plants and we model only existing technologies at that time. In addition, we impose historical initial and final storage capacity of ZRB reservoirs allowing the model to produce an increase/decrease of storage over the 12 months of simulation (all simulation settings are explained in section 4.5). The new modelling configurations are implemented both in *Calliope_base* and in *Calliope_hydro* and results are then compared with real energy data from IEA. Among the years of data available, we decide to simulate the system behavior of 1998 and 2005. Results obtained are very interesting for the case of Zimbabwe; scenarios settings for this country are summarized in table 5.5.

Table 5.5: *Simulations settings for Zimbabwe.*

Year	Coal capacity factor	Kariba hydrological scenario		
		Cumulated inflow	Initial level [m]	Final level [m]
1998	57.8%	$3.24*10^7$	483	480
2005	55.0%	$2.85*10^7$	484	479

Starting from 1998 outcomes (fig.5.17), we can notice how *Calliope_base* is still overestimating hydropower up to the 59% of the total production, while *Calliope_hydro* hydroelectric share is almost equal to the real 29% from IEA. 1998 was a quite wet year, thus we can expect a high hydropower production. Actually, the regulator of Kariba decided to fill the reservoir along the year, thus reducing the water available for hydropower production. This strategy cannot be modelled by *Calliope_base* where hydropower is implemented in a traditional way. In *Calliope_base*, the impressive amount of power production exceeding the demand is exported to cover Botswana energy requirements. This happens

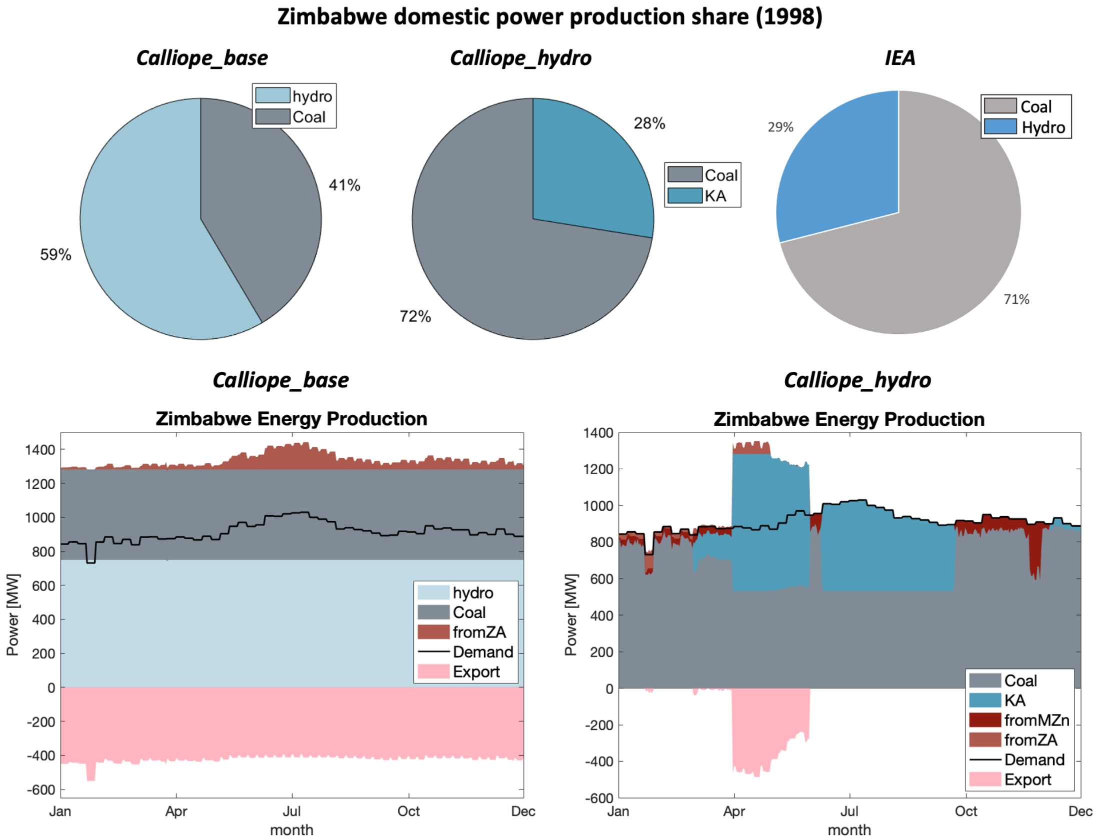


Figure 5.17: *Zimbabwe energy production comparison between Calliope_hydro, Calliope_base and observed IEA energy data (1998).*

in lower measure for the simulation performed by *Calliope_hydro*, showing how water availability affects not only ZRB hydropower producers but also the importing countries.

Regarding the experiment perfomed selecting the year 2005, results can be discussed following the same considerations stated above. Looking at the power production outcomes (fig.5.18), we can notice that again *Calliope_base* overestimates hydropower production, while *Calliope_hydro* hydroelectric share is still closer to the real one. Inflow was not particularly abundant in 2005 and Kariba level decreased along the year. Hydropower production is higher than the one in 1998 and the difference between *Calliope_base* and *Calliope_hydro* is less evident. Anyway, referring to power production timeseries, one can appreciate *Calliope_hydro* allocation of hydroelectric generation.

This last section consisted of a validation of *Calliope_hydro* results, which confirmed to better reflect real energy system behavior compared to *Calliope_base*. Accounting for water availability and storage constraints certainly leads to more reliable modelling and more realistic results.

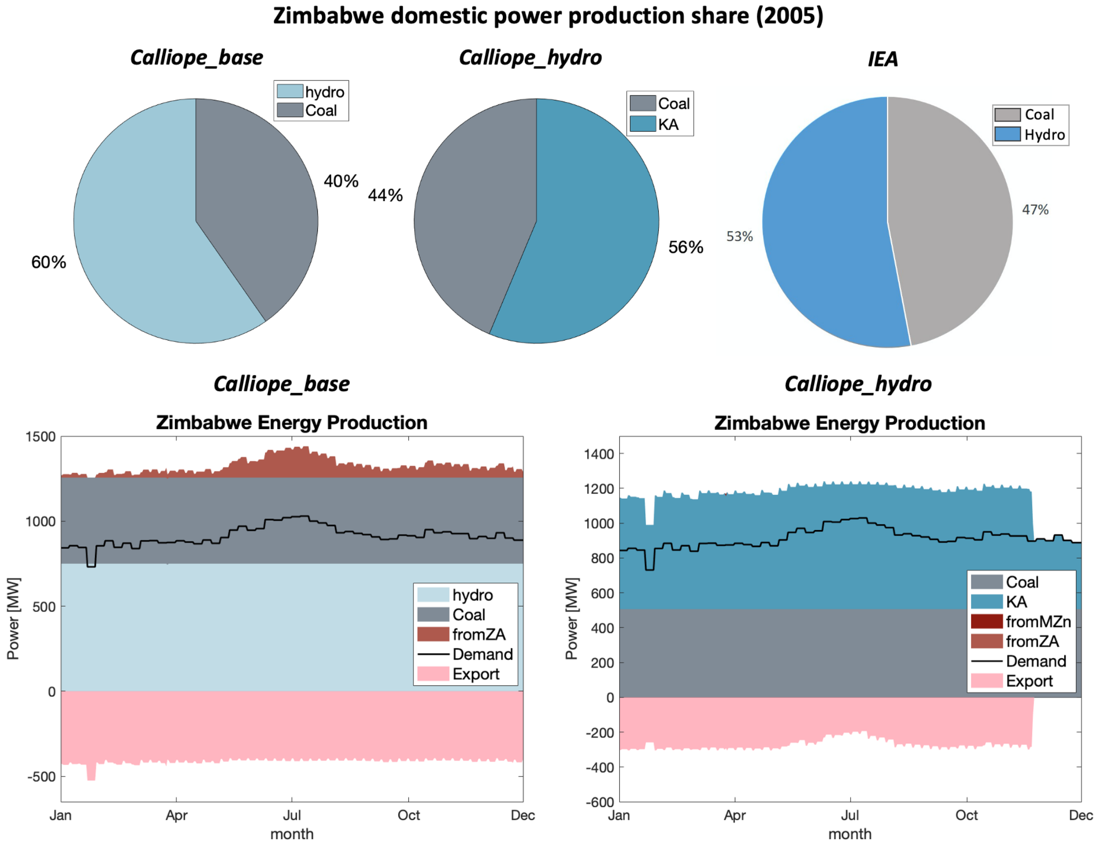


Figure 5.18: *Zimbabwe energy production comparison between Calliope_hydro, Calliope_base and observed IEA energy data (2005).*

6

Conclusions

Background and motivation

This work took inspiration from the Sustainable Development framework, which sets out a wide range of economic, social and environmental objectives calling for integrated solutions. Ensuring secure supplies of energy and water are among the great challenges that society faces and the linkages between them are increasingly recognized.
Indeed the key to improve hydropower sustainability is an integrated approach for water and energy supply planning and management; that's why in this work we wanted to improve hydropower description in energy models by integrating the hydrological constraints related to water availability and reservoirs dynamics under a water-energy nexus perspective.

Energy models vs Water models

At present, there are deep differences between how energy and hydrological systems are modelled:

- In energy models the spatial scale is often political and it rarely overlaps with hydrological basin boundary;
- In energy models the time resolution has to match with the electricity market or long-term interannual economic analysis, while in hydrological models the time resolution follows the basin dynamic;
- In energy models hydropower is modeled under the assumption of hydrological stationarity, neglecting water resource variability;

- In hydrological model, the energy system is not considered in its entirety and hydropower production is usually maximized without considering energy grid.

To implement the nexus approach, these differences in methods and models have to be mitigated. In this work we adopted the "full-integration" approach, describing in a single model both the water and the energy systems. In order to achieve this goal, we exploited all the potentiality of the existing components of the open source energy model Calliope. In this work we used this open source optimization software because of its high spatial and temporal resolutions and its fast learning curve; in this way we were able to build and explore several energy and hydrological scenarios. The possibility to customize the native code allowed us to implement new feature and will enable future code development moving towards a more detailed description of water-energy systems.

The case study

We applied our modelling strategy for the four main reeservoirs of the Zambezi River Basin as part of the overall Southern African Power Pool (SAPP): Itezhitezhi, Kafue Gorge Upper, Kariba and Cahora Bassa. Despite coal-fired power dominates the regional power mix, nearly 40 GW of hydropower could be potentially deployed in the short to medium term. Thus hydropower will play a key role in the future as well as at the present: indeed many SAPP members are already strongly dependent on hydropower production (Zambia and Mozambique rely on hydro for 80%; Zimbabwe hydropower production accounts for 60% of the total).
The Zambezi River Basin (ZRB) has one of the most variable climates of any major river basin in the world; such high hydrological variability makes the entire ZRB highly susceptible to extreme droughts and floods that occur nearly every decade, with considerable impact on the sustainable economic growth of eight riparian countries, on a rich and diverse natural environment and obviously on hydropower production in the basin.
Our approach where hydropower is modelled basin-wide considering the whole energy system is fundamental for this region. This is because of the importance of water resource for its countries and the relevance of new projects that may influence the whole energy system considered.

Methodology

We have shown how a detailed hydrological description of hydropower production could lead to a completely different optimization of the energy system.

In such a way hydropower generation would reflect water resource availability and variability while satisfying energy demand and grid constraints.
We proceeded as follows:

1. We modelled a multiple cascade reservoirs system including inflow patterns, maximum and minimum storage limit, maximum release constraint and spillways.

2. We included non-linear hydrological constraints thanks to external computation and iterative integration of evaporation losses and time-variable hydraulic head.

3. We ran the model exploiting a 20-years timeseries of historical inflows in order to evaluate model outputs variation under different hydrological scenarios.

In this way we built a very first water-energy model in Calliope environment which we named *Calliope_hydro*. This model represents a first attempt to introduce hydrological constraints into the under development energy model Calliope. There are several potentials and as many aspects to be further improved: going from the spillage technology definition to the convergence of storage trajectories among the iterations of the external loop. Nevertheless, results showed that model weaknesses do not largely affect the outcomes.
Spillways impacts mainly Cahora Bassa and the amount of water that eludes the system is in the range of 0.2% and 7% of the total volume entering the reservoir. Despite this limitation, Cahora Bassa hydropower plant produces always at its nominal capacity, revealing that spillage does not affect the energy system.
Similarly, the missing convergence of storage timeseries at the end of the external loop has a limited effect on model outcomes. This issue mainly affects dry scenarios, because the lower availability of water in input relax storage management constraints, letting *Calliope_hydro* more freedom for water resource allocation. Nevertheless, power production shares are constant among iterations; what slightly changes is the different allocation of hydropower production over time but hydroelectric generation trend is preserved, including period of suspended production.

Results

In order to best highlight the potentials of our work, we compared *Calliope_hydro* results with the equivalent energy-model *Calliope_base*, that we built traditionally without including hydrological constraints. In order to discuss about as

more accurate results as possible, we took as reference the simulation under inflow scenario of 1996-1997.
Calliope_hydro confirmed to allocate hydropower production according to water availability, while *Calliope_base* reproduced an unrealistic dispatchability of energy production, letting hydropower produce at its nominal capacity every time of the year. This was dramatically highlighted by Zambia and Zimbabwe power production resulting from *Calliope_base*, in which hydropower is deeply overestimated. In this way, hydroelectric generation in Zimbabwe covers the 82% of energy requirements in *Calliope_base* and only the 27% in *Calliope_hydro*. In *Calliope_base*, Zambia hydropower production exceeds its energy demand of more than 29% of its total production as export to Zimbabwe; this amount of energy will contribute to Botswana power demand supply. In *Calliope_hydro* it is not feasible anymore, and Zambia has to cover its energy needs with 11% of coal-based generation. As a consequence, Botswana has to satisify its power demand through a 100% coal-based generation, while in *Calliope_base* it was importing 89% of clean hydropower energy.
We can assert that reservoirs modelling integration ensures an improved management and planning of energy system while respecting hydrological constraints, giving a better perception of how the energy system is working considering resource availability.

Adopting a wider perspective and considering all results among the different scenarios, Zimbabwe resulted to be one of the countries in which the variation of the energy mix is much more evident. Kariba production goes from the 16% up to more than 82% in wettest conditions, with a coal-based generation respectively of 69% and 0.01%. Zambia power production rely mainly on hydropower for most of scenarios, with a maximum coal share of 12.1% in driest conditions. High variability can be seen in hydropower production contribution of each reservoir, especially for Kafue Gorge (with a share in the range of 43.7% and 64.8%) and Kariba (with a production share between 14.7% and 32.2%). On the contrary, Mozambique generation mix is slightly influenced by dry or wet seasons thanks to Cahora Bassa location and design.
Water availability not only influences hydropower producers countries, but also importers which deeply rely on water-based energy. This is the case of Botswana, which under driest conditions has to satisfy its energy needs with a 100% coal based generation.
In conclusion, *Calliope_hydro* results among all scenarios gave us the idea of how the energy mix of some african countries deeply depends on water availability. This enables the possibility of exploring power pool response to dry or

wet periods, improving energy system management.

Calliope_hydro confirmed its potential also in simulating real energy system behavior. An additional analysis was made comparing *Calliope_base* and *Calliope_hydro* results with real energy data from IEA. For this purpose we selected a specific year for simulation, we imposed a minimum energy production for coal power plants, we modelled only existing technologies at that time and we set historical initial and final storage capacity of ZRB reservoirs. Among the years of data available, we simulated the system behavior of 1998 and 2005. Results showed that *Calliope_hydro* power production approaches the real one while *Calliope_base* largely overestimates it. This was particularly highlighted by Zimbabwe power production in 1998: *Calliope_hydro* hydropower share of 28% differed only 1% from IEA data, while *Calliope_base* one resulted as 59%.
Calliope_hydro confirmed that accounting for water availability and storage constraints certainly leads to more reliable modelling thus more realistic results. Further improvements can be done in this direction in order to achieve a flawless fully integrated water-energy model.

Future developments

Despite weaknesses, our water-energy model *Calliope_hydro* is a very first tool which optimized the energy system while respecting reservoirs hydrological constraints for hydropower production.
Further improvements of our work regards developing Calliope code with a deeper programming knowledge, introducing new features or completely new technologies. Additionally, the trade off between temporal resolution and simulation time horizon could be investigated, in order to possibly extend the model simulations to 5 year horizon; in this way the simulation period would better capture the reservoirs dynamics. Finally the external loop stability can be refined; storage timeseries convergence could improve and a more accurate and fully exhaustive hydrological description could be finally reached.
Beyond technical improvements, many other aspects can be improved. For example, investigating the SAPP future development could be very interesting. Many projects are starting with the aim of improving energy interconnections among countries. An impressive increase in population and consequently in energy demand is predicted for the next years, but the big potential for renewable technologies has not been explored yet. Finally, an improved description of the SAPP energy system can be obtained with more detailed data about each country; opening up the possibility of increasing the numbers of nodes and improving the spatial resolution of the model.

In this thesis we implemented a full-integration nexus modelling strategy; although this is the perfect approach, a model where water resources and energy system planning and management are optimized simultaneously, with the level of detail required by the complex phenomena involved, has not been implemented yet because of its high computational cost. *Calliope_hydro* is the very first attempt to overcome this issue. Big efforts have to be done in this direction in order to improve the sustainability of both regulatory of existing dams as well as the planning of future ones, especially for developing countries.

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A

Additional material

A.1 Reservoir water mass balance check

In section 3.3.1 we explained how our modelling scheme is respecting the mass balance of the water storage system. The issue was related to the direct waterflow between the *supply water* technology (SW) and the *conversion_plus* one (C+) skipping the reservoir, while in real systems all the inflow enters the reservoir before being released to the hydropower plant (HP). To prove the reliability of this model, we compared the multiple reservoirs configuration applied to just one storage with the single reservoir configuration; the two schemes are compared in fig.A.1.

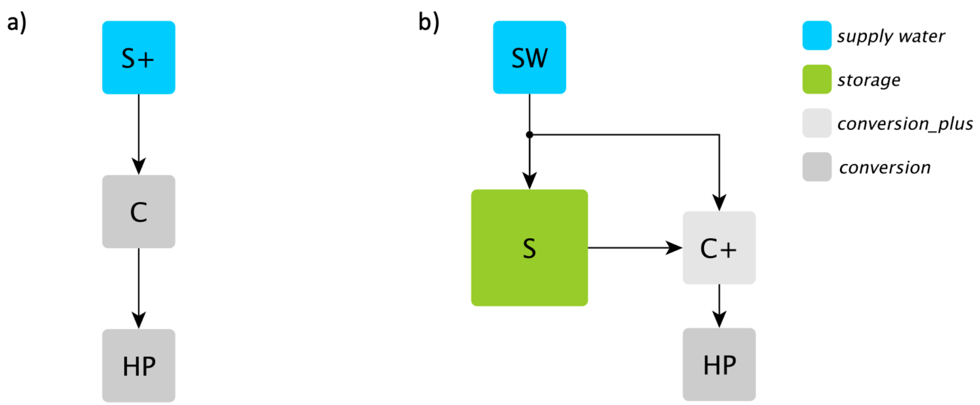

Figure A.1: *Comparing the ideal modelling scheme (a) with the feasible one (b).*

We already explained why modelling scheme "b" is not affecting negatively

our model. In this section we will prove what we already stated comparing our results with the ones of modelling scheme ”a”. In Calliope, the *supply_plus* technology (S+) is able to have a resource timeseries as input and an energy storage system incorporated, perfectly mimicking the water reservoir dynamics. This would be the ideal modelling scheme, but it works only for a single reservoir configuration. The issue arises when dealing with a multiple cascade reservoirs system, in which the inputs of downstream water storage is the sum of its natural inflow and the release from upstream reservoirs. The *supply_plus* technology is not able to deal with multiple cascade configuration, that's why we adopted the modelling solution ”b”.
Since the two different schemes work for a single reservoir system, we can evaluate the differences between model ”a”, which perfectly respect reservoir dynamic, with our modelling choice (model ”b”). Running the two different system under the same scenario, we obtained the the same optimization solution except for very few hours of the overall simulation horizon. Fig.A.2 shows the power production obtained by the two models; it is evident that differences

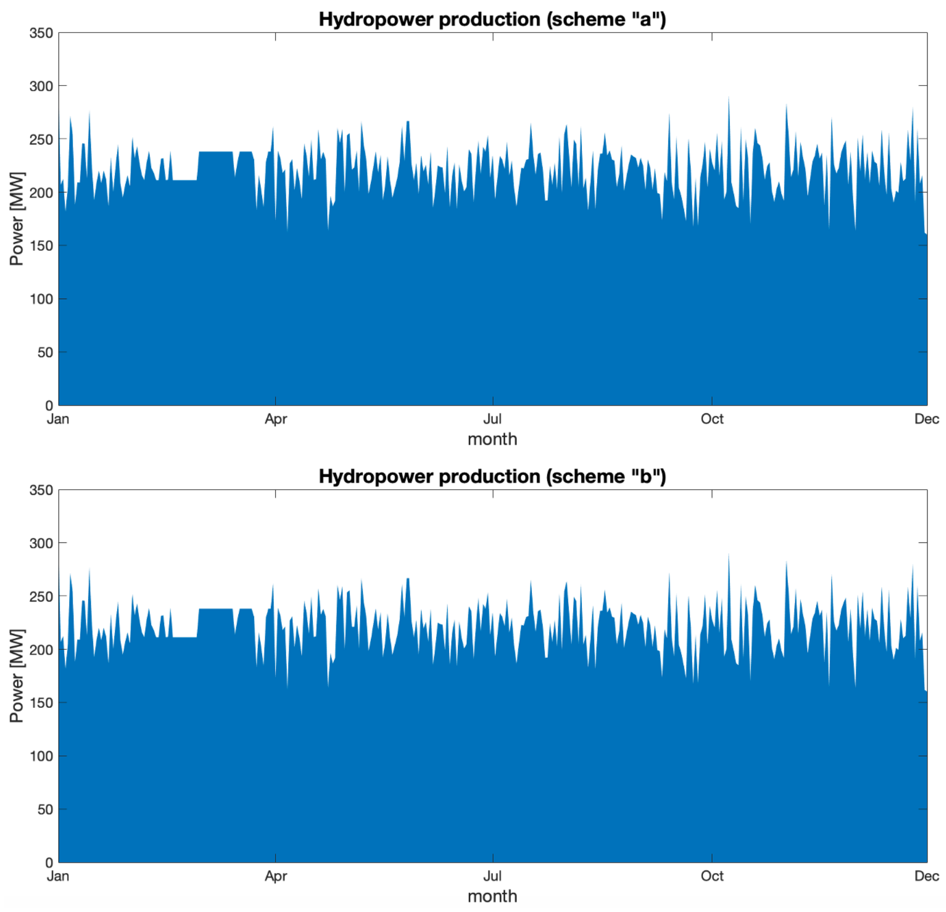

Figure A.2: *Comparing results of the ideal modelling scheme (a) with the feasible one (b).*

in allocating hydropower production are negligible even if adopting two different modelling schemes. It demonstrates the goodness of our modelling configuration despite there is a direct connection between inflows and hydropower plants.