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Analysis of the water-power nexus in the Southern African Power Pool

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Contents

Foreword

Increasing water stress will intensify competition between water uses. A lack or an excess of water may undermine the functioning of the energy and food production sectors with societal and economic effects. Energy and water are inextricably linked: we need “water for energy” for cooling thermal power plants, energy storage, biofuels production, hydropower, enhanced oil recovery, etc., and we need “energy for water” to pump, treat and desalinate. Without energy and water, we cannot satisfy basic human needs, produce food for a rapidly growing population and achieve economic growth. Producing more crops per drop to meet present and future food demands means developing new water governance approaches.

The Water Energy Food and Ecosystem Nexus (WEFE-Nexus) flagship project addresses in an integrated way the interdependencies and interactions between water, energy, agriculture, as well as household demand. These interactions have been so far largely underappreciated. The WEFE-Nexus can be depicted as a way to overcome stakeholders’ view of resources as individual assets by developing an understanding of the broader system. It is the realisation that acting from the perspective of individual sectors cannot help tackle future societal challenges.

The overall objective of the WEFE-Nexus is to help in a systemic way the design and implementation of European policies with water dependency. By combining expertise and data from across the Joint Research Centre (JRC) it will inform cross-sectoral policy making on how to improve the resilience of water-using sectors such as energy, agriculture and ecosystems.

WEFE-NEXUS objectives

- Analyse the most significant interdependencies by testing strategies, policy options and technological solutions under different socio-economic scenarios for Europe and beyond.
- Evaluate the impacts of changing availability of water due to climate change, land use, urbanization, demography in Europe and geographical areas of strategic interest for the EU.
- Deliver country and regional scale reports, outlooks on anomalies in water availability, a toolbox for scenario-based decision making, and science-policy briefs connecting the project’s recommendations to the policy process.

How is the analysis done?

JRC experts use a broad range of models and sources to ensure a robust analysis. This includes water resources and climate models to understand current and future availability of water resources, and energy models and scenario employed to understand and forecast current and future energy demands and the related water footprint of the energy sector.

The results from these models are expected to provide i) understanding the impacts of water resources on the operation of the energy system, and vice versa, ii) spatial analysis and projection of water and energy requirements of agricultural and urban areas in different regions, iii) producing insights for a better management of water and energy resources.

What is this report about?

The WEFE projects aims to provide a detailed insight of the water-power nexus in all African power pools, since the power system is the most water-intensive part of the energy industry. This technical report provides the results of the model-based analyses carried out for the Southern Africa Power Pool (SAPP), building on the approach previously used by the JRC for the West (De Felice et al., 2018), and for the North, Central, and Eastern Africa Power Pools (Pavicevic and Quoilin, 2020).

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Abstract

The countries in the SAPP, albeit heterogeneous in terms of their economic development including the maturity of their energy systems, face the joint challenge of having to expand and transform their electricity infrastructure. This is on the one hand driven by the need to serve demand that is expected to grow sharply in order to provide for electricity access, and to keep up with projected population growth and economic convergence. On the other hand, changing climatic conditions have immediate implications for the electricity generation in the SAPP. A large share of countries rely on hydropower as their primary generation option and currently major rivers, such as the Zambezi or the Congo feeding the water storage reservoirs in the region, are subject to significant variability of their mean annual discharge. This variability, which is particularly high in the fall season, is confirmed through the analyses carried out for this report.

To help understand and address these challenges this report provides a knowledge base by describing the SAPP power system for the years 2016 and 2017 and by testing the performance of the SAPP through a model-based analysis against a broad range of inflows to the hydro reservoirs derived from an ensemble of 39 historic climatic years. Our analysis, which is openly available through the JRC Data Catalogue, reveals that the resulting inflows vary considerably, in particular during the fall season, and that this variability affects the hydro generation output differently depending on which SAPP country is considered. On the low end of the spectrum is the share of hydro generation in South Africa which remains pretty constant reaching up to 5%, while on the upper end is the share of hydro generation in Mozambique which shows a considerable variation between around 40% to more than 100%, where the latter case is associated with the climatic years where Mozambique acts as an exporter of electricity to the SAPP. The variable hydro output significantly goes along with economic impacts in terms of unserved energy and high electricity price levels; this is in particular the case when a country is both relying on high shares of hydro generation and not interconnected to other countries in the pool as it is the case for Angola and Malawi in the study period 2016/2017. In these two countries, as well as in the Democratic Republic of Congo, which according to our analysis lacks adequate generation capacity and is only weakly interconnected, unserved energy and electricity prices can increase by a factor of three to four with low levels of hydro generation output. For the other SAPP countries the variability is more modest since they broadly benefit from (excess) availability of South African base load generation capacity, most notably coal that can be made available to the other SAPP countries through the interconnected system.

This report also investigates the possible consequences of a capacity shortfall in South Africa, which has happened historically due to extreme flooding events, and sheds light on the benefits of expanding interconnections among SAPP countries by implementing all currently planned projects, both in comparison to the reference situation and to the capacity shortfall. Our results show that capacity shortage in South Africa would negatively spill-over to other SAPP countries in terms of increased levels of unserved energy and electricity prices.

Contrary, an increased interconnectedness of the SAPP power system allows the currently unconnected countries to participate in the gains of pooling resources and overall, by providing more flexible paths for the electricity to flow, increases the resilience against electricity supply interruptions. By comparing the capacity factors of interconnectors for a broad range of hydro-climatic conditions, we identify promising candidate projects for new interconnection capacity additions or expansions respectively that can be assessed further in more granular analyses. In terms of socio-economic impacts, increased interconnectedness is reflected in an overall significantly reduced and smoothed distribution of electricity price and unserved electricity levels.

1 Introduction

1.1 African water-power nexus: challenges and opportunities

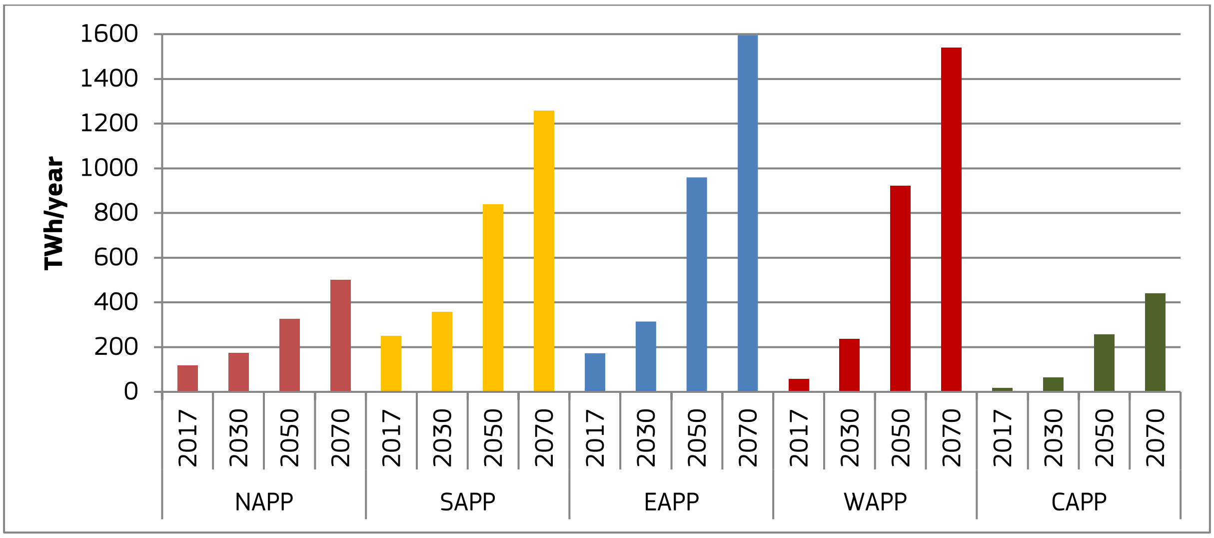
This report focusing on the SAPP is part of a larger series of JRC studies investigating the water-power nexus in Africa. The objective of this series is to carry out the analyses for all African power pools to provide a complete coverage of the African mainland power system. De Felice et al. (De Felice et al., 2018) have addressed the situation in the West African Power Pool (WAPP) and Pavicievic and Quoilin (Pavicevic and Quoilin, 2020) covered the North (NAPP), Central (CAPP) and Eastern (EAPP) African Power Pool through their analysis. This activity is carried out as part of the WEFE Nexus project at the European Commission's JRC.

African energy issues have received increased attention on the European policy agenda and this focus has been further elevated with the recent communications on the European Green Deal (European Commission, 2019), which stresses that 'climate and environmental issues should be key strands in relations between the two continents', and the communication on a comprehensive strategy with Africa (European Commission, 2020).

Africa is currently confronted with a variety of challenges in the electricity sector. According to the International Energy Agency (IEA, 2017) close to 600 million people are still without access to electricity in sub-Saharan Africa (SSA). Those who have access to electricity often suffer from supply interruptions. World Bank data (The World Bank, 2019) shows that countries in SSA experience annual electricity outages ranging from 50 up to more than half of all year's hours per year. Different reasons tend to cause the blackouts and brownouts in the electricity grid; chief among them are infrastructure failures and capacity shortages when the expansion of the generation fleet cannot keep up with demand growth. Since in many African countries hydropower accounts for a large fraction of the total generation capacity, periods with low water inflows are another major thread for generation inadequacy and thus supply disruptions. These supply disruptions go along with negative economic and health consequences. When electricity is not available either load has to be shed, triggering for instance economic processes to be put on hold, or diesel-generators have to be ramped-up. The latter response also negatively affects air-pollution levels and can be three times more costly than grid-electricity according to a study (Farquharson, Jaramillo, and Samaras, 2018).

While the current situation is already challenging anticipated future developments can be expected to raise the challenge even further. As shown in Figure 1, according to a study conducted by KTH Stockholm (Pappis et al., 2019) for the JRC, the electricity demand in the different African power pools is expected to increase at exponential rates (in some cases more than a factor 10) This increase is driven by the concurrent expected developments of *increasing electricity access rates*, *population growth* and *economic convergence* leading overall to higher per capita electricity consumption. On top of that, climate change could further aggravate demand for energy services (van Ruijven, De Cian, and Sue Wing, 2019) and alter rainfall patterns (IPCC, 2014; Beilfuss, 2012) leading to further challenges on the supply-demand equation.

Figure 1: Electricity demand projections per power pool in the reference scenario developed by KTH Stockholm.



Source: (Pappis et al., 2019)

Given this starting point and the scale of the transformation that is required, the challenge is extraordinarily ambitious. To keep up with the pace of growing demand and access needs, in a business-as-usual setting it is likely that a substantial fraction of that would be met by fossil energy carriers, in particular coal, which in the SAPP region have an ample availability. The proven benefit of coal, as shown through the case of South Africa, is that it can provide for comparatively stable access to electricity at moderate costs and large scales. Such a scenario however, from a European perspective, could substantially thwart European and global efforts to achieve carbon neutrality in the coming decades. However, given the legitimate interests of Africa to achieve economic converge and energy access during a similar timespan[1] additional compliance with the climate-neutrality objectives will likely only be achieved if carbon-free or neutral energy supply will be considered at least as beneficial as the carbon-intensive alternative. Fortunately, Africa also possesses very favourable conditions for renewable energies and in particular the geographical latitude of the continent offers high levels of solar irradiation that allow for low costs in converting this to electricity. To put this into a perspective, the current mid-range cost of Solar PV in Germany is in the order of 48 Euro per MWh (BloombergNEF, 2019). Leaving all parameters unchanged, except replacing the capacity factor of 11% with a reported value of 26% for South Africa (CSIR, 2017) would reduce the LCOE to about 20 Euro per MWh.

This illustrates that very affordable alternatives exist. Moreover, a recent study by Wilson et al. (Wilson et al., 2020) showed that low-carbon technologies that are smaller scale, more affordable, and can be mass-deployed are more likely to enable a faster transition to net-zero emissions. This suggests there is a strong potential for Africa to leapfrog the build-up of a large scale fossil infrastructure and directly invest into modern, and clean forms of energy supply that are also capable to provide distributed access to these services. Europe could aid this process though knowledge exchange and capacity building, as it is already happening, and by helping to establish the regulatory conditions that allow for the deployment of these technologies at such favourable costs. A strong framework for such a partnership has been laid-out through the communication on a comprehensive strategy with Africa (European Commission, 2020).

1.2 The Southern African Power Pool

Recognising the benefits of cooperation across countries to confront the energy challenges dating back since the late 1980's, power pools have gradually emerged in Africa. Today five power pools are established in Africa that comprise the Central, Eastern, North, West and Southern African Power Pool respectively. Each mainland African country is member in at least one power pool and few countries are members in or more pools. The aims of the power pools are to jointly plan and operate the power systems across the countries, which is reflected in growing levels of interconnections and the gradual establishment of a market-based coordination approach. There are also plans to establish interconnections between power pools.

Historically, the Southern African mainland has been weakly electrically interconnected, allowing only for very small volumes of electricity exchange. The first exchanges took place between the Democratic Republic of Congo, Zambia and Zimbabwe in the 1960s' followed by an interconnection between Mozambique and South Africa in the 1970s' (Wright and Coller, 2018). This resulted in two distinct (northern and southern) interconnected systems in Southern Africa. With the Cahora Bassa Dam in Mozambique finished in 1974 the interconnection with South Africa provided a window into how pooling the large coal resources in the southern part (South Africa, Botswana) with the hydro rich North (Congo and Zambezi basins) could be beneficial for the whole region. It was in 1995 when the northern and southern systems were interconnected through a 400 kV link between Zimbabwe and South Africa. This year marked the establishment of the Southern African Power Pool under the Southern African Development Community (SADC). Its coordination centre was set-up in Harare, Zimbabwe, and its twelve member countries, which are shown in Table 1 below, comprise all mainland members of the SADC. At the time of writing, Angola, Malawi, and Tanzania do not have connections yet with another member, but new electricity lines are in the planning and expected to be operational within a foreseeable time-span.

[1] https://au.int/en/agenda2063/goals

Table 1: The SAPP: Members and key statistics.

Country	ISO-3 code	Population (thousands)	GDP per capita (current USD)	Electricity access (percent)	Avg. outage (hours/year)
Angola	AGO	30 809	3 432	41.9	760
Botswana	BWA	2 254	8 258	62.8	830
DR Congo	DRC	84 068	561	19.1	830
Lesotho	LSO	2 108	1 299	33.7	No data
Malawi	MWI	18 143	389	12.7	No data
Mozambique	MOZ	29 495	499	27.4	80
Namibia	NAM	2 448	5 931	52.5	No data
South Africa	ZAF	57 779	6 374	84.4	50
Swaziland (Eswatini)	SWZ	1 136	4 146	73.5	No data
Tanzania	TZA	56 318	1 061.	32.8	670
Zambia	ZMB	17 351	1 539	40.3	180
Zimbabwe	ZWE	14 439	2 147	40.4	280

Sources: (SAPP; Farquharson, Jaramillo, and Samaras, 2018; The World Bank, 2019)

In terms of market development the SAPP is regarded the most advanced among the African power pools (Infrastructure Consortium for Africa, 2016), having been the first among the pools to establish a competitive day-ahead market in 2009 and intraday and forward market segments subsequently. The SAPP member countries though are quite heterogeneous when it comes to population size and status of economic development. As can be seen from Table 1 population size ranges from about 1.1 million in Swaziland to around 84 million in the Democratic Republic of Congo. On another end, the Democratic Republic of Congo lags behind in terms of economic development reflected by the third lowest GDP per capita and an electricity access rate slightly below 20 percent. Similar low performances can be seen for Malawi and Mozambique. The other big country in the SAPP in terms of population is South Africa which is also its economic powerhouse. An important enabler for that is the highest electricity access rate among the countries of almost 85 percent. Botswana, Namibia and Swaziland in comparison also show a good performance in these two indicators. Assuming, in line with Sustainable Development Goal 7 (which calls for universal access to affordable, reliable and modern energy services by 2030) a further improvement and convergence across SAPP countries of these indicators provides an indication in which SAPP countries the strongest drivers of future electricity demand can be expected.

As already mentioned above, power generation in the SAPP largely relies on two types of energy carriers: coal from the fields in South Africa and Botswana and water stemming from the Congo, Orange and Zambezi rivers and their branches. These two forms of power generation are both water intensive, exposing the electricity generation in the SAPP region to water scarcity risks through for instance heat waves or competition over water resources. Coal, as is the case for all thermal plants, requires water to cool down plants' high temperatures, so that a water shortage or too warm water can impede this process. Hydropower plants convert running/falling water – mechanical energy – into electrical energy – without water there is no energy source to convert (Wang, Schleifer, and Zhong, 2017).

Particularly in recent years diminished and late or irregular rainfall together with long-term temperature increases have affected the supply of water for hydropower generation. Several examples for this are provided in Box 1. This is to illustrate that essentially all of the SAPP countries are affected by water-related impacts on their electricity generation and in conjunction with other causes experience extended periods of electricity supply interruptions (compare Table 1). The economic costs of these power outages are high and have been estimated at 5–7% of the GDP for Malawi, South Africa and Tanzania (Conway et al., 2017). The water related risks for the SAPP could become even stronger in the future. With the new hydro project currently in the pipeline there will be a growing concentration of hydropower generating capacity in a single basin - the Zambezi basin - from about 70% now to around 85% in 2030 (Conway et al., 2017).

Box 1: Events of electricity supply disruptions in the SAPP caused by droughts and inconsistent rainfall.

— "In late 2015, the Tanzanian government was forced to shut down all its hydroelectric plants following droughts that dried up many of the country's dams, or left them with dangerously low water levels. As a result, the country generated only 12% of the power it regularly consumed leaving millions of people in the dark" (Lara, 2018).

— "In 2016, the largest hydroelectric plant in sub-Saharan Africa, Mozambique's Cahora Bassa, also found itself in trouble. Two years of drought conditions brought water levels to record lows, down to 34% of full dam capacity. The impact went well beyond Mozambique, as about two-thirds of power generated at the facility is sold to South Africa and Zimbabwe" (Lara, 2018).

— "Also located on the Zambezi river is Zambia's largest hydroelectric plant, the Kariba is located upstream of Cahora Bassa and supplies roughly 40% of Zambia's power demand. Unsurprisingly, in the same year of Cahora Bassa's record lows, power generation at Kariba fell by a whopping 75%. Currently, Lake Kariba, stands at historically low water level just barely above the amount need to keep the hydro power pants running" (Lara, 2018).

— Low water levels in Lake Malawi have reduced the water flow on the Shire River causing a capacity shortfall of 150 MW in Malawi's hydro power generation (about 35 % of peak demand). A similar situation occurred in Namibia where available hydro capacity became as low as 90 to 160 MW instead of the nominal capacity of the Rucana power plant (ESCOM).

— In 2008 South Africa experienced a significant drop of more than 20 percent in it electricity generation (Carson et al., 2018). Rather than by drought, South Africa was affected by heavy rainfall which flooded and muddied the coalmines and silos, which affected the coal supply for the power plants (UNECA, 2018). In the end of 2019 coal mines were flooded again by heavy rains triggering another series of power cuts on top of an already challenging situation.

Sources: (Lara, 2018; ESCOM; Carson et al., 2018; UNECA, 2018).

1.3 Scope and limitations of this report

The objective of this report is to add to a knowledge base for analysing and understanding implications of climate-driven freshwater availability for power system planning and operation in Africa and, in the context of this report, in particular in the SAPP. From an analytical modelling angle, such an analysis has two main components: The use of hydrological tools and methods to analyse the availability of freshwater and the use of power system modelling to study the implication on the power system, whereby usually both components to a certain extend are featured in each analysis though with different weights and details. As such, our analysis adds to a body of preceding and ongoing analyses reflecting the interest and relevance to analyse the implications of and for hydropower in Southern Africa, in particular in view of the projected demand increase and climatic changes.

For instance, Conway et al. (Conway et al., 2017) investigate the risk of concurrent climate-related electricity supply disruption taking into account cross regional correlations and Kling et al. (Kling, Fuchs, and Stanzel, 2015) explore the impact of water resources development and climate scenarios on Zambezi River discharge through detailed hydrological modelling including water routing. In our work, we benefit from the runoff data for Southern Africa generated with the JRC's LISFLOOD model for a long range of historic climatic years. We do not go into a detailed analysis of this data, e.g. by looking at cross-correlation, but process it further to make it usable as input for the power system modelling. On the power system modelling end, several institutions (IRENA, 2015; SAPP Planning Sub-Committee, Economic Consulting Associates, Norconsult A/S, Energy Exemplar, EiHP, 2017; Spalding-Fecher, 2018) conduct analyses of the operation and future development of the SAPP power system and particular the latter work by Spalding-Fecher considers in detail the implications of climate change and irrigation development in the Zambezi River Basin. The World Bank (World Bank, 2017) has conducted a detailed analysis, including modelling, of the water-energy nexus in South Africa.[2] Falchetta et al. (Falchetta et al., 2019) provide a comprehensive overview of studies dealing with water-energy nexus issues in south-Saharan Africa.

Our analysis in this report is more similar in scope to the power system modelling work referred to above, but we also think that different elements of our work add some new and unique features to the knowledge base:

[2] This study only came to our attention recently so that not all the knowledge provided in it could be fed into our analysis.

— We combine a detailed, well-established hydrological model that generates runoff data for a large ensemble of climatic years with a power system model with hourly resolution incorporating all the relevant operational constraints and covering the whole region. That allows for a detailed analysis of climate-driven hydro variability on operational patterns and economic consequences of variable hydro availability. In the other analyses, the system boundaries usually were focused on either of the perspectives and the other one was only considered more rudimentarily. An exception is the work of Spalding-Fecher (Spalding-Fecher, 2018), who however had more a long-term perspective and did not model an hourly resolution and focused on the Zambezi basin.

— In our work we follow a coherent approach for all of Africa, i.e. we employ the same modelling framework for all five African power pools, facilitating inter-comparison and interoperability.

— We make all the used datasets and modelling tools publically available through the WEFE collection in the JRC Data Catalogue[3] allowing other analysts to investigate further specific questions related to the sustainable electricity supply in Africa, thereby building on our work without having to start from scratch.

1.3.1 What can – and cannot - be addressed through our framework

The combination of detailed modelling tools combined with rich data sets offer the opportunity to conduct realistic simulations of the Southern African Power System. We however do not attempt to replicate exactly the performance observed in reality, which would be a too tall order due to several limitations. On the one hand, not all the relevant constraints are incorporated in the model – partially due to computational limitations to keep the model solvable. For instance, we do not model the electricity network within a country leading to the simplified assumption that all installed capacity is available to serve demand in this country. In reality, however, countries lack (available) power lines connecting all of the inner-country supply with demand, which can lead to generation inadequacy and thus forced load shedding even though enough generation capacity would be available at the country level. On the other hand, we have to cope with limited data availability to validate all of our input parameters. For instance, we could not find official statistics to verify the (technical) outages of power plants in the SAPP, fuel prices in the different countries or inflows to all the reservoirs. Another issue when it comes to data is the model calibration for a reference year. Not all the required input data were available for the same years or it was not always clear whether they are based on coherent assumptions where they refer to the same year. In the (yet) comparatively small, in terms of installed capacity and peak demand, power systems in the SAPP (except South Africa) it can however make a significant difference where an additional power plant is included in the analysis or not.

Under these given caveats, we aim to calibrate the reference case of the model to represent the situation in the SAPP in the year-range 2016/2017. Even though this does not fully replicate the reality, we think it offers – within plausible parameter ranges – a realistic scenario of the current situation in the SAPP and is therefore well suited to compare the reference case against sensitivity variants. Thus in this report in addition to the reference case we explore through sensitivities the implications of changes in a few parameters of key relevance for the SAPP. These sensitivities should not be considered future policy scenarios, but rather as a tool to answer 'what-if' type of questions.

1.3.2 Questions to be addressed and scenarios modelled

In the context of the current and anticipated future challenges in the SAPP, as described in section 1.2, we use our framework to model the following four scenarios in order to shed light on questions of high relevance for the SAPP (a scenario taxonomy is provided in Table 2 below):

1. The ***Reference Scenario*** aims to provide a realistic scenario – within plausible parameters ranges – of the situation that has been characteristic for the Southern African Power Pool in 2016/2017. The main question to be addressed by this scenario is as follows: ***How does the reference power system of 2016/2017 perform under a broad range of climatic conditions?***

2. A ***Connected Scenario*** that is implemented as a sensitivity variant of the Reference Scenario. Specifically in this scenario, it is assumed that all currently planned interconnection projects in the SAPP would be implemented. All other parameters correspond to the Reference Scenario. The main underlying question is as follows: ***Given the vast challenges the member countries of the SAPP are currently facing, to which extend can increased interconnections between the SAPP***

[3] https://data.jrc.ec.europa.eu/collection/id-00134

countries create benefits by better pooling resources and strengthening resilience (e.g. avoided load-shedding)?

3. A ***Capacity Outage Scenario*** that is implemented as further sensitivity variant of the Reference Scenario. In this variant, it is assumed that similarly to events that have occurred in the recent past, the availability of the South African thermal fleet would be reduced below normal for a certain period. This would also have consequences for other SAPP countries that traditionally relied on South Africa for bulk supply (UNECA, 2018). Analyses have shown that more extreme climatic conditions going along with an abnormally hot summer with well-below average or more concentrated rainfall, could become a more regular pattern in this already very arid area, and therefore lead to extended droughts and flooding. The underlying question is ***how the SAPP would be impacted economically (at the power system level) through a spilling-over a supply capacity shortage in South Africa***. The availability of the coal fleet is assumed to be lowered to 50 percent during this period

4. ***Combined Connected and Capacity Outage (Con_Out) Scenario***. This variant combines variants two and three. Reduced availability of the South African coal fleet has been shown in the past to affect the resilience in the whole SAPP region. The question is ***how far a higher connection between SAPP countries could help alleviate the negative impacts by better pooling the other available resources to create back-ups***.

Table 2: Scenario taxonomy.

Scenario Taxonomy		Interconnections	
		2016/2017	Future/Planned
Thermal plant availability	2016/2017	Reference	Connected
	Reduced	Capacity Outage	Connected & Capacity Outage (Con_Out)

Source: JRC, 2020

2 Methodological framework and input data

2.1 Modelling approach[4]

The analysis in this report builds on the use of power-system modelling making use of an established suite of modelling tools developed and operated within the JRC (Burek, van der Knijff, and de Roo, 2013; Hidalgo González, Quoilin, and Zucker, 2014; Kavvadias et al., 2018; Pavičević et al., 2019; Fernández-Blanco Carramolino, Kavvadias, and Hidalgo González, 2017). More specifically, the hydrological rainfall-runoff LISFLOOD Model and the Unit Commitment and Dispatch Model Dispa-SET are coupled in a sequential order to obtain the modelling results: In the first step, the LISFLOOD model is solved. LISFLOOD simulates the hydrological processes in a catchment including flood forecasting, assessing the effects of river regulation measures, effects of land-use change and effects of climate. This run-off data is further processed to derive inflow data, which serve as input for the Dispa-SET model, at the locations of power plants and their corresponding reservoirs. For the work in this report a new formulation of the Dispa-SET model that includes a Mid-term Hydro-Thermal Scheduling (MTS) module in the pre-processing has been used. The MTS module calculates the optimal water management under perfect foresight and passes on this parameter as a guiding curve to the main Dispa-SET unit commitment and dispatch module. Due to the high number of simulation runs conducted for this work, the MTS module has been run in a set-up with time-steps of 24 hours to lower the computational burden.

2.2 Input data

This section describes the most important input data for the power system modelling.

2.2.1 Electricity demand

In order to estimate electricity demand time-series the same methodology applied in De Felice et al. (De Felice et al., 2018) is used. In this approach, due to the lack of historical data for all the countries analysed, synthetic hourly load profiles are estimated through a regression combining available energy statistics with meteorological data. For this analysis the hourly profiles have been updated by re-scaling them to match energy demand balances for the year 2017 published by the IEA (International Energy Agency, 2018). Demand balances include final gross electricity consumption as well as losses to account for all electricity that has to be generated. The statistics published in the SAPP Annual report (SAPP, 2017) are used as a complementary data source.

2.2.2 Discharge levels and reservoir inflows

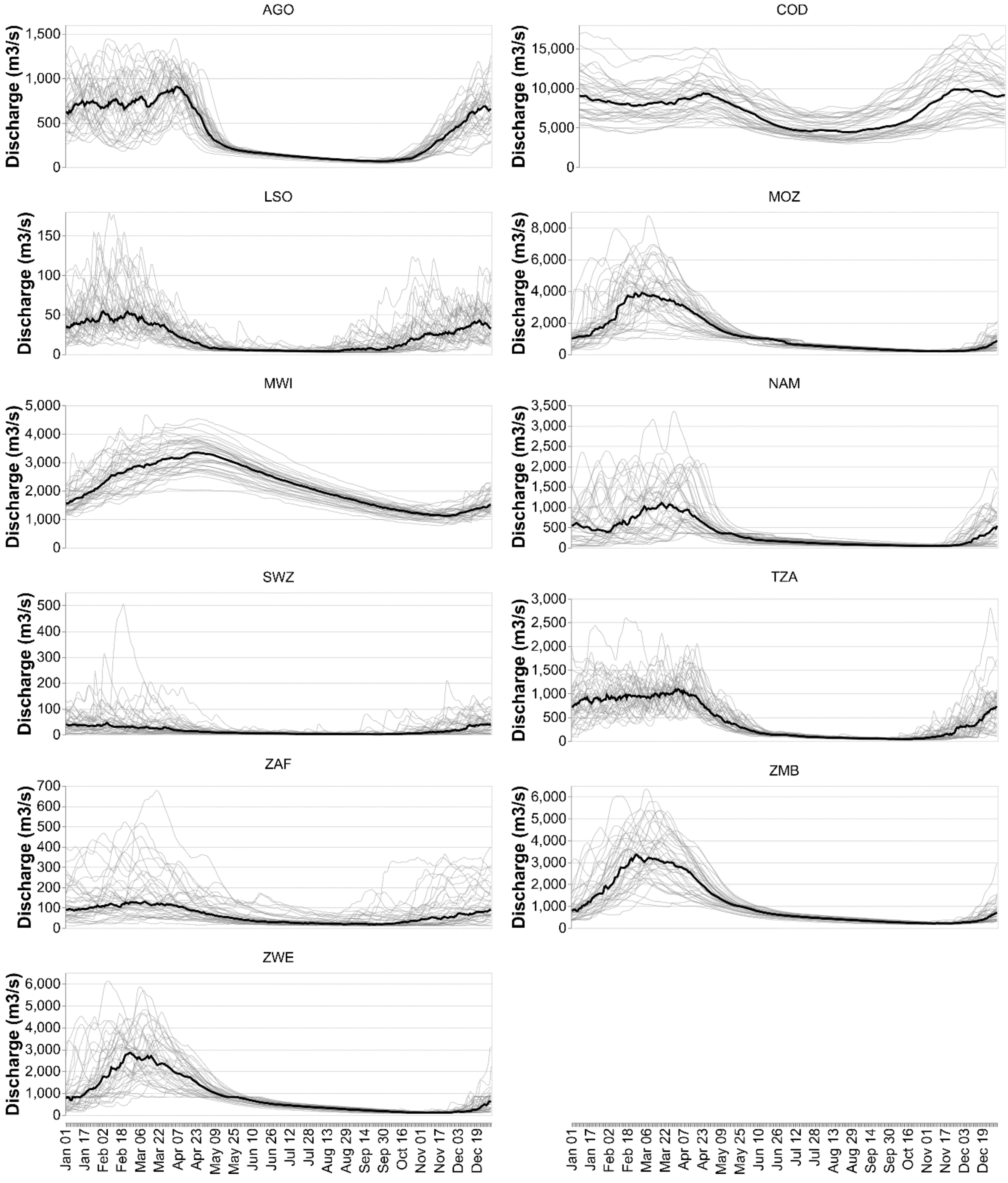
Figure 2, which shows the aggregated discharge levels of all hydro plants considered in a country that have been extracted from the LISFLOOD runs, reveals several interesting patterns. By tendency over all climatic years the discharge levels follow a pattern where they increase over the summer months and reach a peak in fall from which they decline again to plateau during winter.[5] During the fall peak, also by far the highest variability can be observed; in some extreme cases the outliers can account for changes in discharge levels in an order similar to the aggregate water availability in the residual year. By comparing the different SAPP countries also important differences can be noted. Whereas in most of the countries the discharge during the dry period reaches very low levels, this reduction appears less pronounced in the Democratic Republic of Congo and in Malawi. Overall discharge levels are found to be highest in the Democratic Republic of Congo benefitting from the massive amounts of water flowing through the Congo River whereas countries further downstream in the SAPP (Lesotho, South Africa, and Swaziland) have the lowest discharge levels. Also a strong similarity between the profiles of the discharge levels in Zambia and Zimbabwe can be spotted. This is explained by the fact that the biggest hydro power stations in the two countries both benefit from the discharge of the Zambezi River into the Kariba Gorge.

While the discharge levels reveal the climatic patterns and variability of water flows in the SAPP they cannot be used one-to-one as inflows to the hydro power plants and their corresponding reservoirs. This is the case since several factors reduce the volume of discharged water that is available for inflows: These include environmental flows, evaporation and most significantly regulated water routing and cascades. Moreover, there

[4] A more detailed description is provided in the annex.
[5] According to seasons in the southern hemisphere.

is generally a strong non-linearity in the rainfall–runoff transformation (Kling, 2017). To arrive at plausible assumptions for the assumption for the inflow values we take a practical approach informed by actually observed capacity factors that have been reported in the work of IRENA (IRENA, 2015). Therefore we have re-scaled, i.e., downscaled the discharge levels to match observed long-term average capacity factors.[6]

Figure 2: Aggregate discharge levels (m³/s) at locations of all considered hydro plants in SAPP member countries.



Source: JRC, 2020

Black line denotes the median year, grey lines the range of all climatic years.

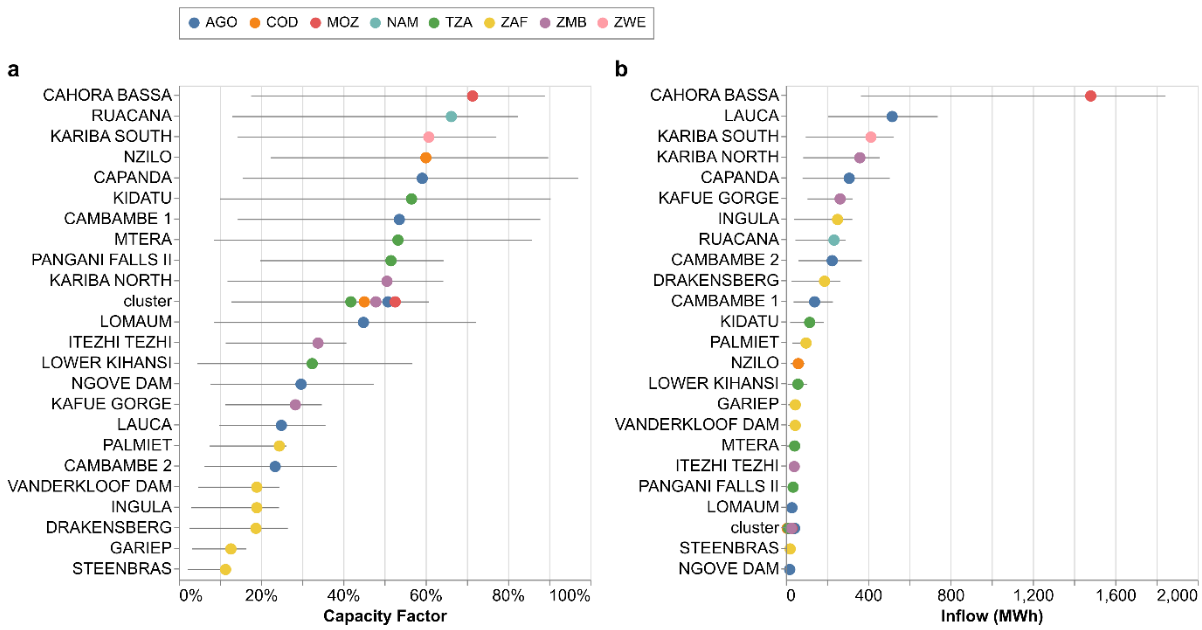
[6] The underlying assumption is that all inflows will be transformed into power generation though potentially time-lagged. It is assumed that such an approach filters out all water uses from the inflows not related to electricity generation. It has to be noted that significant uncertainties about the validity of the resulting inflows remain in the absence of a dataset to validate hydro related values.

Subsequently for use in the Dispa-SET model these inflow values denoted in m³/s are transformed into MWh by applying the following equation, where besides net_inflow the nominal head is the other power plant specific parameter.

$$inflow_{mwh} = net\_inflow_{m3/s} * 3{,}600 * 1{,}000 * 9.81 * Nominal\_Head/3.6e9$$

Figure 3 shows, for the cases of individual hydropower plants with reservoirs, the resulting capacity factors (panel a) and inflow levels (panel b) as long-term average over all the climatic years. It can be seen that the hydro plants in South Africa have the lowest inflows which can be explained by the fact that they are situated further downstream in the SAPP where runoff is generally lower in the Orange basin, but also since most of them operate as pumped-storage schemes, so that their generation is not only reliant on external inflows. The grey lines denote the inter-quartile ranges. It can be seen that these ranges tend to be higher for comparatively large inflows, which can potentially be explained by the fact that all regions in the SAPP are exposed to dry periods.

Figure 3: Inflows (GWh) at locations of all considered hydro reservoirs in SAPP member countries.



Source: JRC, 2020

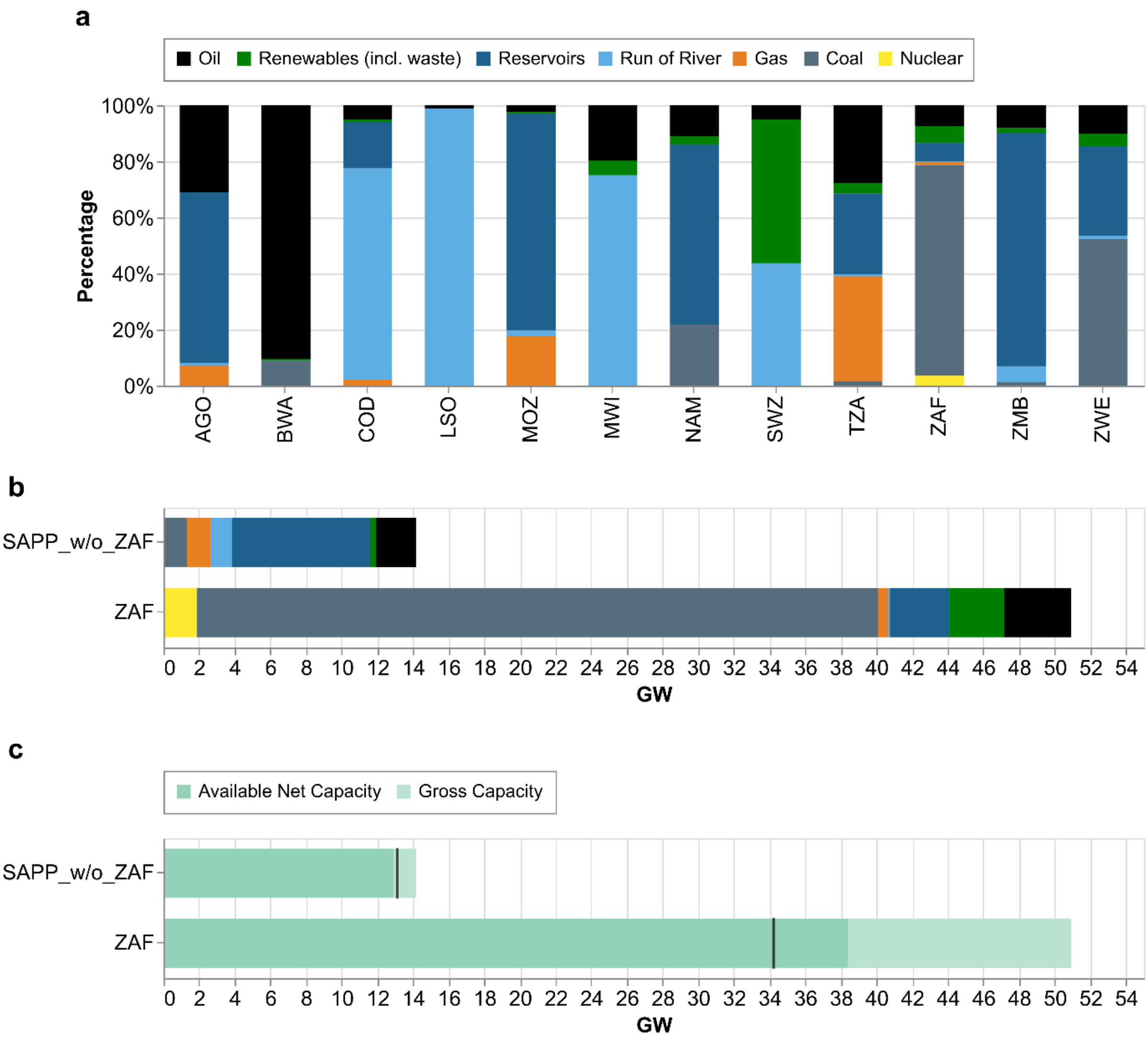
Circles denote long-range averages, grey lines the inner-quartile ranges of all climatic years. Hydro power plants with a capacity below 50 MW in each country have been clustered.

2.2.3 SAPP power plant fleet

2.2.3.1 Installed and available capacities

The power plant fleet in the SAPP is dominated by a few key generation options. A look at panel a of Figure 4 reveals that hydro based generation capacity from hydro dams (HDAM) and run-of-river (HROR) accounts for the highest share of generation capacity in most of the SAPP countries. This is followed by fossil-fuelled generation capacity from coal and oil/diesel, which dominate in the generation mixes of South Africa, Botswana and Zimbabwe. Another perspective can be gained from panel b, which shows the capacity breakdown in absolute terms split by South Africa and all remaining SAPP countries. From this panel it can be seen that South Africa alone accounts for about three-quarters of the total installed generation capacity in the SAPP and there coal capacity has the highest absolute share among all generation technologies, in fact by far higher than all other options together.

Figure 4: The SAPP power plant fleet.

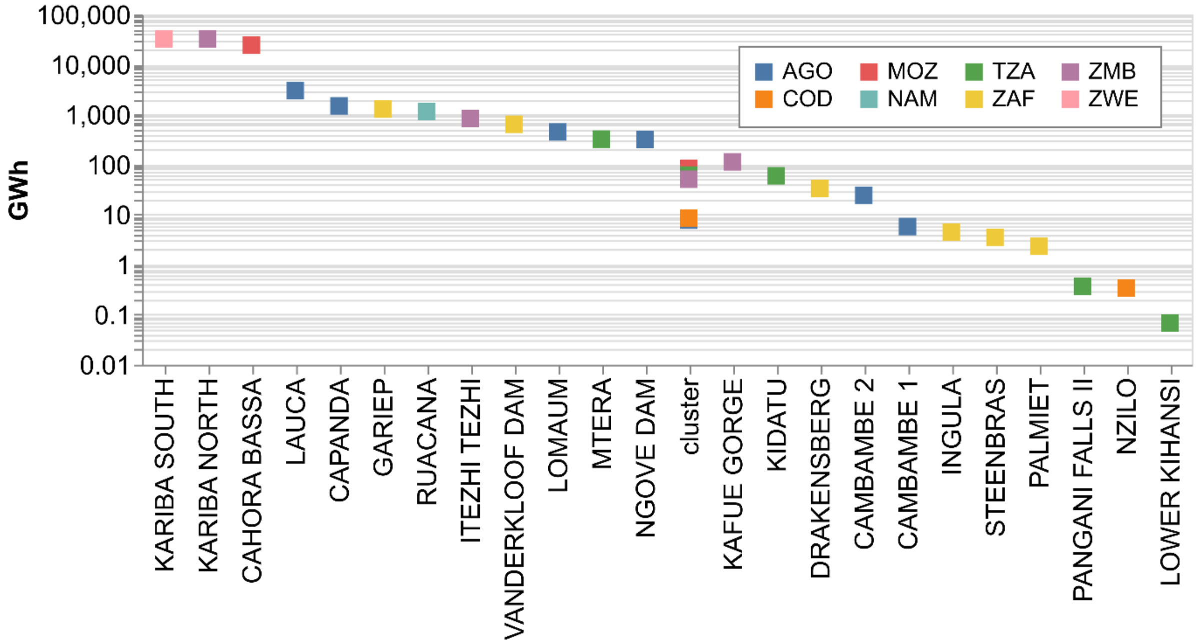


Source: JRC, 2020

However, as became evident already from the discussion in chapter 1, not all of this capacity is permanently available for generation. The assumptions taken on net available capacity are displayed in panel c. Since no data at unit level could be obtained availabilities have been estimated at fleet level per country based on the SAPP annual statistics as the share of net capacity in the installed capacity (SAPP, 2017). Only for South Africa where the share of available capacity in the statistics appeared (too) high a different source has been used. Here the same average outage value of 28 percent, as assumed in the mid-term system adequacy outlook of Eskom, the South African utility, is used (ESKOM, 2016). The outage factors have been applied only to the dispatchable part of the fleet – excluding the variable renewable and hydro. The reason is that for the latter generation option outages are already reflected in the assumed values for the capacity factors. Therefore, due to the higher share of dispatchable generation capacity, the reduction of gross capacity appears more pronounced in South Africa. In panel c the black bar displays the peak demand. In conjunction with the available information of gross and net capacities the observation can be drawn that South Africa has a significant buffer of gross capacity over peak demand so that also with an outage rate of 28 percent demand can be served at system level at any time. On the contrary in the remaining SAPP countries installed capacities at system level are much closer to the margin of peak demand so even a small reduction of gross capacity leads to generation inadequacy in times of peak demand. This deficit could be further exacerbated when for instance hydro generation units are not available to produce at their rated capacities.

2.2.3.2 Reservoirs for water storage

Figure 5: Storage sizes (GWh) of reservoirs linked to hydropower plants.



Source: JRC, 2020

Hydro power plants with a capacity below 50 MW in each country have been clustered.

One important element of flexibility for hydropower plants is the availability of a reservoir to store water. This allows managing and, over longer periods, transforming inflows into electricity output as it is done in the MTS run with the Dispa-SET model. The assumed sizes of the reservoirs vary considerably – one the one hand Lake Kariba as the world's largest man-made reservoir with an assumed storage capacity of more than 33,000 GWh is capable of storing the Zambezi's entire mean annual inflow volume (Beilfuss, 2012). On the other hand the reservoirs of the pumped-storage schemes in South Africa are designed for frequent charges and discharges and thus do not require such big reservoir sizes. The three smallest reservoirs are probably run-of-river type of schemes with small dams and reservoirs as buffer and are therefore classified as reservoirs in the technology database.

2.2.3.3 Cooling technologies

Water for cooling is mostly relevant for larger thermal power plants. In this report we distinguish between three general types of cooling technologies: dry-cooling, once-through-cooling and tower-cooling systems. Larger power plants such as coal plants typically use tower-cooling systems whereas plants of the latest generation are often based on dry-cooling systems. Smaller power plants that have less cooling requirements typically are also based on dry-cooling systems. Once-through cooling due to the higher water needs is often applied with seawater. Based on the type of cooling technology and their location specific factors for water withdrawals and consumption are derived which are based on the JRC's work on current and projected freshwater needs of the African energy system (González Sánchez et al., 2020). A table with plant-specific factors is provided in the annex.

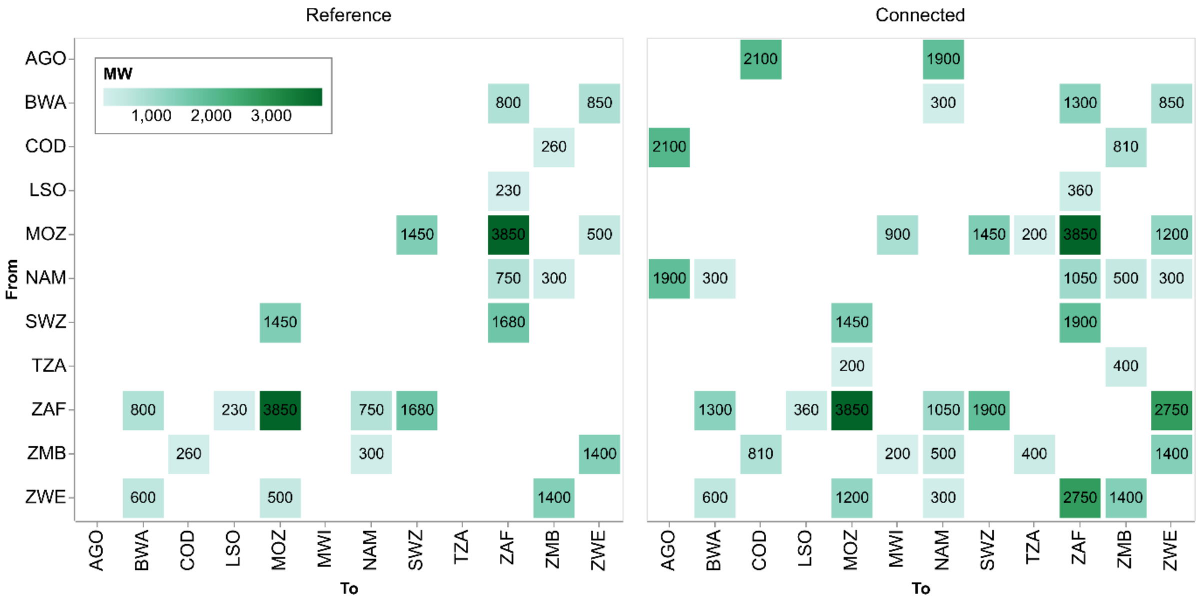
2.2.3.4 Fuel prices

Technology-specific fuel prices are based on the parameters reported in the Integrated Resource Plan, which is the electricity planning exercise, conducted regularly in South Africa (South African Department of Energy, 2016). These values are complemented through country specific components based on the SAPP Pool Plan (SAPP Planning Sub-Committee, Economic Consulting Associates, Norconsult A/S, Energy Exemplar, EiHP, 2017).

2.2.4 Electricity network interconnections

The assumed interconnection capacities are shown in Figure 6. In the reference case interconnections are based on the situation in 2016/2017. Here it can be seen that South Africa is the most interconnected country allowing several of the other SAPP countries to benefit from the relatively stable and moderate cost supply of South Africa's coal fleet. South Africa and Mozambique share by far the highest interconnector capacity on a single border, which allows for the import of electricity produced by the Cahora Bassa Hydro Power Plant. Three countries, Angola, Malawi and Tanzania, do not have interconnections yet. In the connected scenario a range of interconnection projects that are currently planned until 2025 are assumed operational. As a result, all SAPP countries are interconnected, new links are added and existing links have been reinforced, allowing for overall higher trade across the pool.

Figure 6: Assumed interconnection capacities in the SAPP in the Reference and Connected scenarios



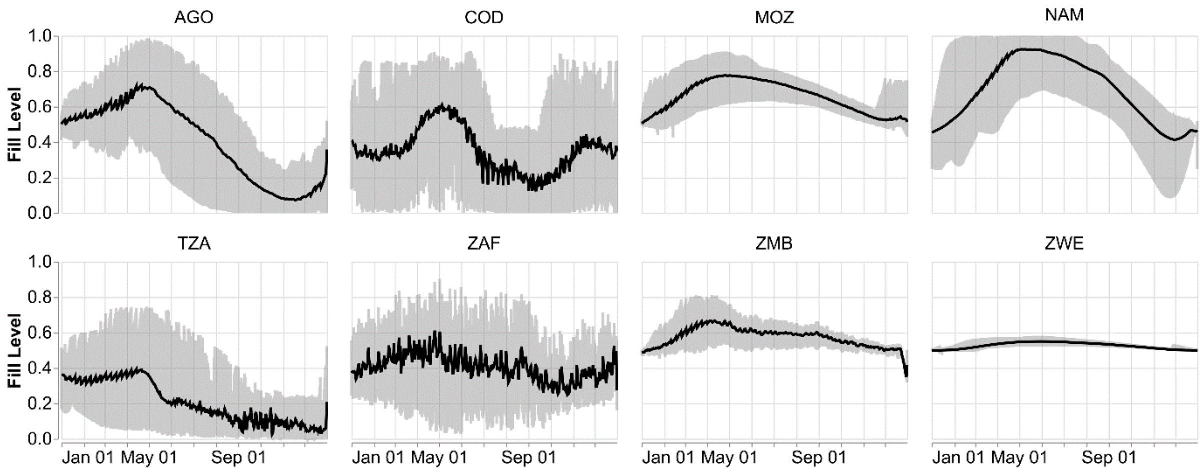
Sources: (Wright and Coller, 2018; Pappis et al., 2019), African Energy Atlas.

3 Results of the reference scenario

3.1 Storage levels

Figure 7 displays the modelled storage levels at country scale in the reference case where black lines denote the median trajectory across all climatic years and grey areas denote the ranges. From these some interesting patterns can be observed. While by tendency all storages are filled at the beginning of the year (in the wetter season between summer and fall) the slopes differ across countries. The fill and discharge rates for instance tend to be much higher for Angola and Namibia than for Zambia and Zimbabwe. One explanation is that the latter two countries gain from access to Lake Kariba, the largest reservoir in the region, and therefore exhibit less variability. Another pattern concerns the 'noise' in the two curves where many spikes refer to higher charging and discharging variability in the short term. This pattern can be seen in particular for South Africa, which is explained by the fact that most of the reservoirs in this country are operated as pumped storage schemes. Also some of the reservoirs experience some limited spillage in the modelling in times of the highest inflows (though not necessarily at the same time) – in the graphs, this is only visible for Namibia which is only operating a single large reservoir – the Ruacana plant – so that no smoothing at country level takes place.

Figure 7: Modelled storage levels as share of maximum capacity in the Reference scenario.



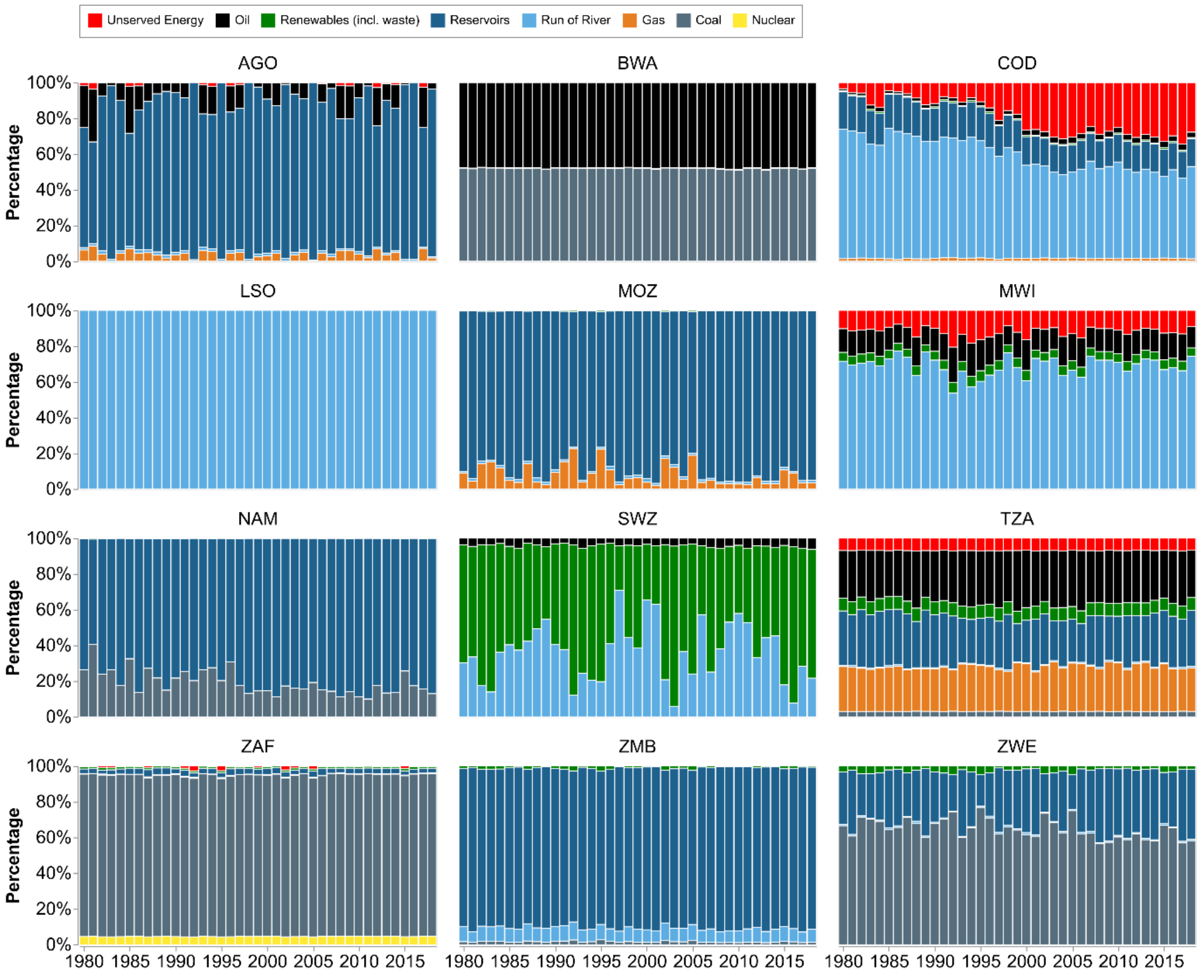
Source: JRC, 2020

Black line denotes mean across climatic year, grey are denotes the range across climatic years.

3.2 Electricity generation

Figure 8 shows the modelled annual energy balances in terms of electricity generated for the range of climatic years. As can be expected the contributions of base-load generation options such as coal in South Africa is rather stable whereas in countries where the dominant generation option is hydro based, such as is for instance the case in Lesotho, Mozambique or Zambia, reveal more cyclical generation patterns. In years with deficit hydro generation (more) oil is dispatched to cover peak demand or to minimise unserved energy (load curtailment + load shedding). Unserved energy is the last resort when available generation capacity is not adequate to serve demand. One can see that this the case in all three SAPP countries not yet connected (Angola, Malawi and Tanzania), but also Botswana and the Democratic Republic of Congo face a generation shortage that in the latter case tends to increase due to lower availability of hydro generation in more recent climatic years. Also in South Africa despite the available generation surplus some smaller load curtailment occurs. This is the case since it is assumed that due to the higher demand by industry a certain fraction can be curtailed at costs lower than the marginal costs of generation so that some curtailment could take place while South Africa still is exporting.

Figure 8: Yearly electricity generation balances in the reference case.



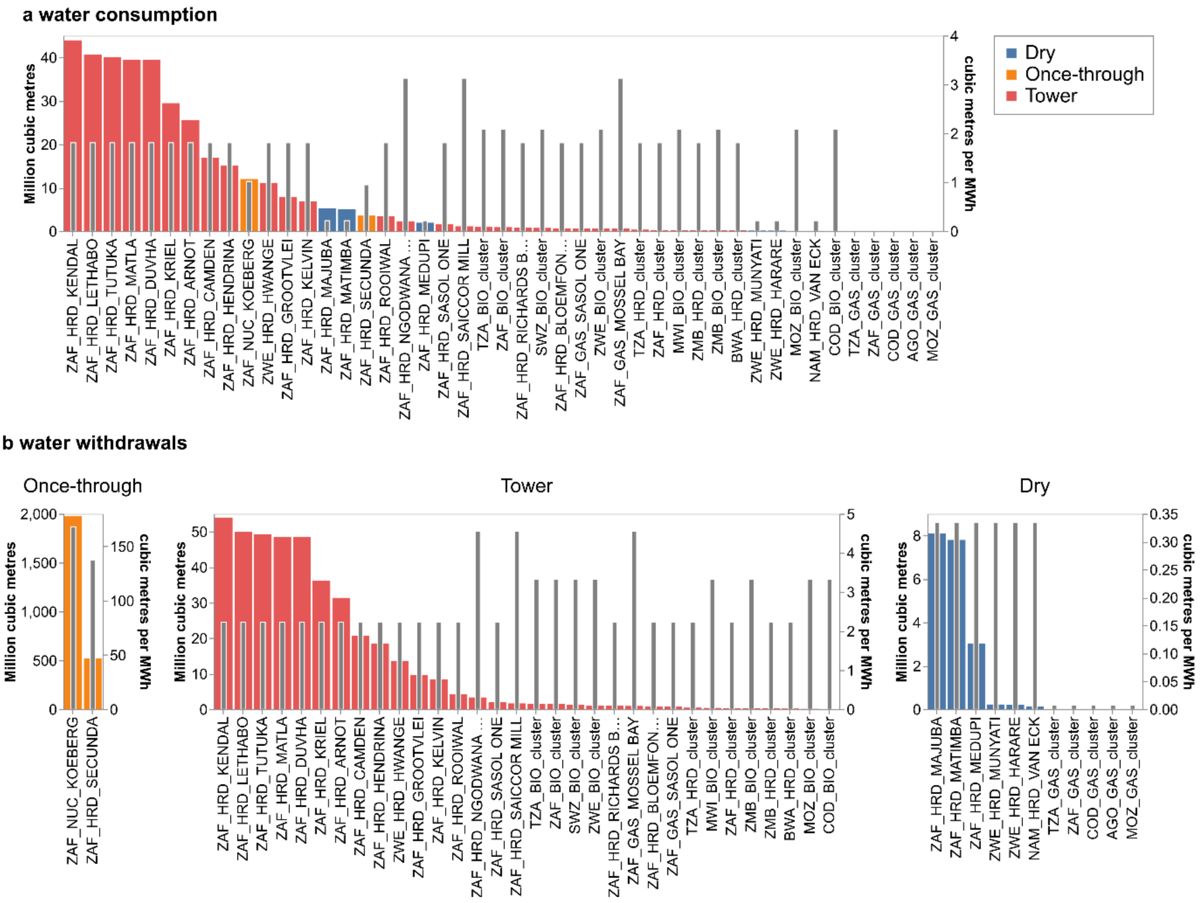
Source: JRC, 2020

Years do not refer to actual historical years but to generation balances of 2016/17 power systems under differ historical, hydro-climatic conditions.

3.3 Water withdrawals and consumption of the thermal fleet

Figure 9 shows the average levels (across climatic years) of water consumption (panel a) and water withdrawals (panel b) resulting from the generation dispatch of the thermal in the reference scenario. On the primary vertical axis, absolute levels in million cubic metres are displayed indicated by the coloured bars and on the secondary vertical axis specific levels in cubic metres per MWh are displayed indicated by the grey bars. For the water consumption in the SAPP displayed in panel a, it can be seen that this is almost entirely driven by the electricity generation of the South African coal power plan fleet. While their specific consumption (secondary vertical axis) is in a similar order of magnitude to that of other thermal power plants the much higher generation output makes the difference here. It can also be seen that biggest power plant in terms of water consumption all use cooling towers whereas the newer generation of coal plants such as Majuba, Matimba or Medupu, that are based on dry-cooling, achieve a much lower specific consumption and therefore also total consumption of water. Concerning water withdrawals a different distribution can be observed from panel b. Due to the significant differences and resulting different scales the power plants are displayed grouped in different columns by type of cooling technology. It can be seen that by far the highest water withdrawals result from once-through type cooling systems. Due to the high volume of water required satisfying the demand with the discharge of a river could be challenging, which is why the Koeberg nuclear plant uses seawater for cooling. For the other two types of cooling technologies the amounts of water withdrawn are much more modest and only slightly higher than water consumption as most of the water consumed can be used in circulation (tower) or water consumption is generally avoided (dry).

Figure 9: Water consumption (panel a) and water withdrawals (panel b) by power plant in the Reference scenario.



Source: JRC, 2020

Please note that the specific water withdrawals in cubic metres per MWh are 168 for the Koeberg nuclear plant and 138 for the Secula coal plant and thus out of the dimension of the axis. Please also note that the Koeberg plat uses seawater for cooling.

Box 2: Potential Water Stress in South Africa

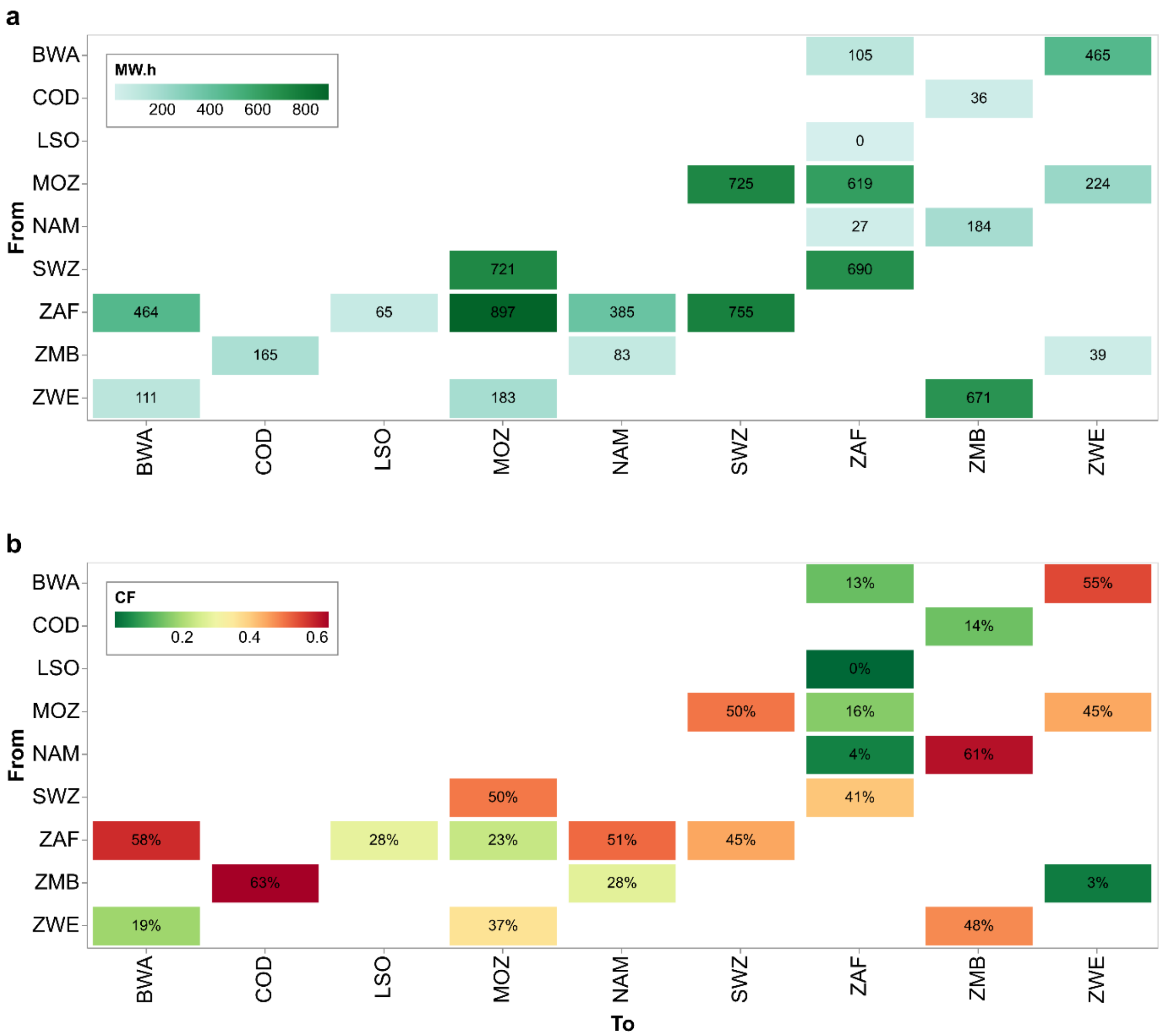
The question to which extent these levels of water consumption and withdrawals can actually contribute to water stress, i.e. a situation where available water could become too low to serve demand, is not straightforward to be answered for the case of South Africa, but it is clear that several perspectives have to be considered. First of all South Africa is a comparatively very dry country that experiences diverging rainfall patterns across the country and has a mean annual precipitation in the order of 500 mm per year, far lower than the global average of 860 mm per year. Therefore already, in general, South Africa is considered a water-stressed country (World Bank, 2017). The majority of coal power stations in South Africa are situated alongside the coal mines in catchment areas that are water scarce, requiring the transport of water between basins for cooling (Hughes et al., 2012). This purpose is mostly served by the Integrated Vaal River System of large dams and inter-basin transfers. Therefore it is not possible to map the water needs of individual power plants to a specific source, but rather aggregate consumption and supply have to be compared. The current water consumption of the South African coal fleet is reported in the order of 300 million m³, which is well in line with the modelled results. Water for power generation accounts for about 2.5 percent all water use in the country (World Bank, 2017) and since it is considered a strategic use it appears likely that it would be prioritized over other water uses that are also supplied by the integrated Vaal river system. Nevertheless given the overall water stressed situation and other essential requirements of water such as in agriculture, efforts are underway to reduce the water footprint of electricity consumption through integrated resource planning and prioritising dry cooling systems in new power plant projects.

3.4 Electricity exchange in the SAPP

Figure 10 displays the cross-border electricity exchanges in the SAPP as averages over all the climatic years. A more detailed breakdown for the individual climatic years is provided in the annex. Panel a shows the flows in absolute terms as averages per hour. From this panel it can be seen that the biggest volumes are exchanged bi-directionally through the MOZ-SWZ-ZAF link. Another major exchange averaging 670 MWh takes place through the ZWE-ZMB link; this one is however not reciprocal as Zambia mostly acts as importer in this case. In general this panel highlights the essential role of South Africa's dispatchable fleet for balancing or substituting variable or respectively more expensive generation in many of the other countries indicated by the exports to and via Botswana, Lesotho, Mozambique, Namibia and Swaziland.

A complementary perspective on cross-border flows is offered by panel b, which displays the capacity factors of the interconnectors, i.e. the share of cross-border electricity exchanges relative to the maximum available capacity. Here it can be seen that due to the different flow limits not necessarily the line with the highest flows as yield the highest capacity factors. In general import capacities to South Arica appear to be among the least utilised interconnectors whereas a shift in color-coding towards red indicates a higher line utilisation factor of the available interconnection capacities. For higher capacity utilisation factors also the likelihood of congestion and thus of forgone benefits of pooling resources increases, such that these lines could be considered preferential candidates for capacity expansion. A look at the panel reveals for instance ZAF-BWA, ZMB-COD, or NAM-ZMB as projects of interest in this regards.

Figure 10: Average electricity exchange volumes (MW.h) between SAPP countries and average interconnection capacity factors across all climatic years.



Source: JRC, 2020

3.5 Selected impacts on techno-economic performance

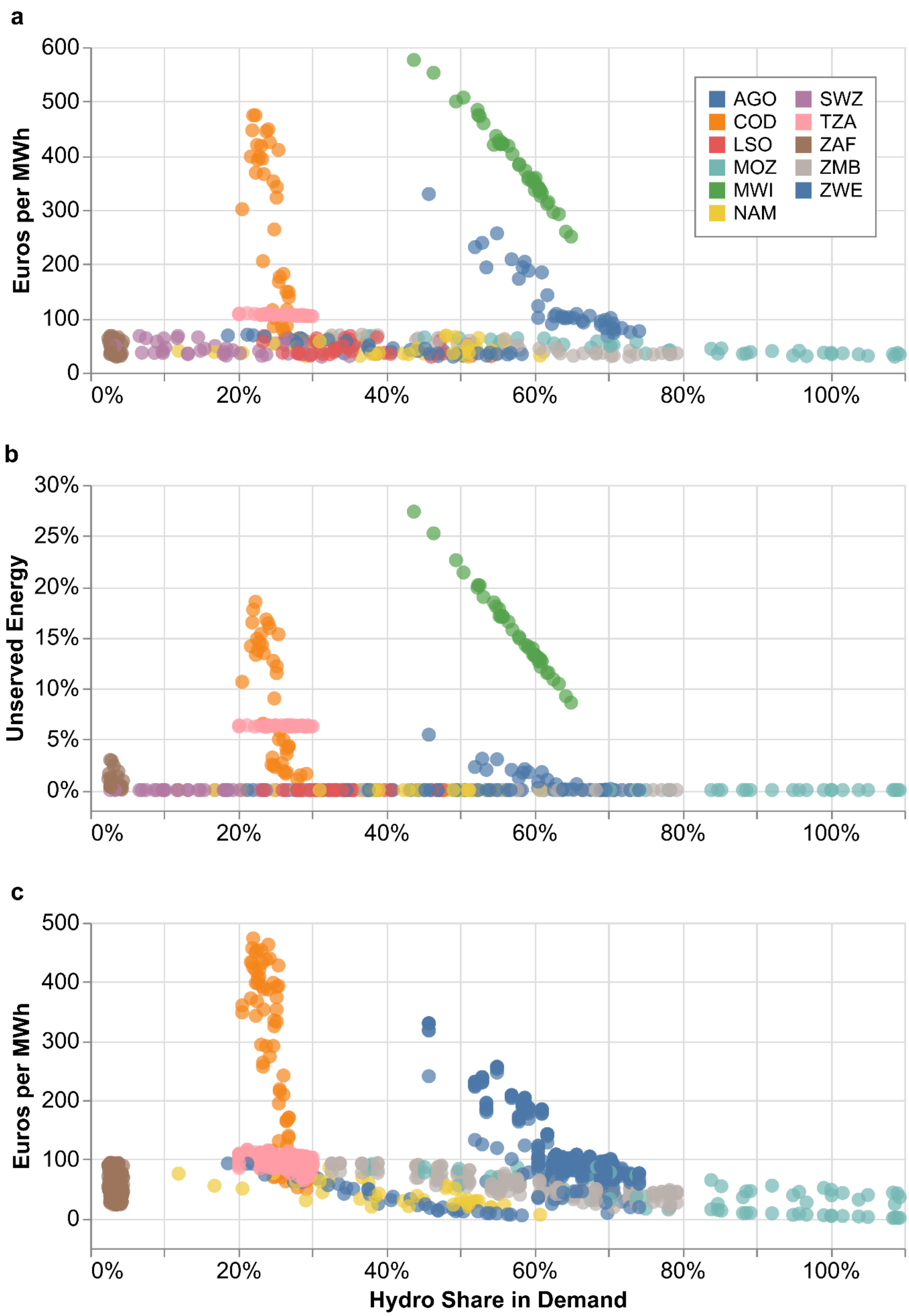
Figure 11 displays selected indicators of techno-economic performance throughout the different climatic years in relation to the corresponding share of hydro generation in annual demand. From panel a, which shows the average annual electricity prices different observations can be made. First of all, by solely looking at the horizontal axis, the ranges of shares of hydro generation in demand can be seen. On the low end of the spectrum is the share of hydro generation in South Africa which remains pretty constant, on the upper end is the share of hydro generation in Mozambique which shows a considerable variation between around 40% to more than 100%, where the latter case is associated with the climatic years where Mozambique acts as an exporter of electricity to the SAPP. As a general trend higher shares of hydro generation – displacing more costly generation – tend to driver lower electricity price. The elasticity however varies strongly between the SAPP countries where the Democratic Republic of Congo stands out followed by Angola and Malawi. For the latter two a clearer correlation can be observed since they are not connected to any other zone in the reference case that could compensate for a low share of hydro generation. For the other countries also some correlation between increased hydro generation shares and lower electricity prices is visible, but in comparison to the countries mentioned before it is much less pronounced. One reason here is that the exports from South Africa can help balance variability of hydro shares in the interconnected SAPP countries leading to a higher convergence of electricity prices.

Further insight on the diverging price levels can be gained from panel b which displays the share of unserved energy comprising both curtailed and shed load. By comparing this to panel a correlation between the amount of unserved energy and average electricity price levels can be ascertained, the linkage being that in situation of scarce supply the electricity price is being set by the value of lost load. Of interest, higher amounts of unserved energy can be seen for South Africa in comparison to other interconnected SAPP countries. The underlying cause is the assumption that in South Africa, due to its higher share of industrial load, electricity customers can offer to curtail a certain share of their load at costs lower than the marginal costs of peak-load generation so that load would be reduced while South Africa would still be exporting. In the reference case the four countries hit hardest by uncontrolled load shedding would be Malawi, the Democratic Republic of Congo, Angola and Tanzania, in particular in the case of Angola and Malawi a higher availability of hydro generation could help to alleviate the situation.

Panel c shows the yearly average water values[7] of the hydro reservoirs in the SAPP countries relative to the share of hydro generation. The water values are derived from the dual variable of the water balance constraint (Fernández-Blanco, Kavvadias, and González, 2017; Fernández-Blanco Carramolino et al., 2017) and therefore carry information about the opportunity costs of storing an additional unit of water (vs. releasing if for electricity generation) for future generation. Two major drivers of the opportunity costs are therefore the alternative costs that would be displaced by releasing the water, indicated by level of the zonal electricity price, and the size and fill level of the reservoir, indicating the flexibility to store / release additional water. By comparison with panel a, as stipulated, a similar pattern for water values is revealed. While this pattern signifies the linkages to the electricity price levels in each country the larger spread of values within each color-coding derives from reservoir specific factors.

[7] The water value of each hydropower plant at each period is mathematically defined as the absolute value of the derivative of the generation cost with respect to the water inflows. It represents the cost of the marginal thermal power plant displaced by hydropower.

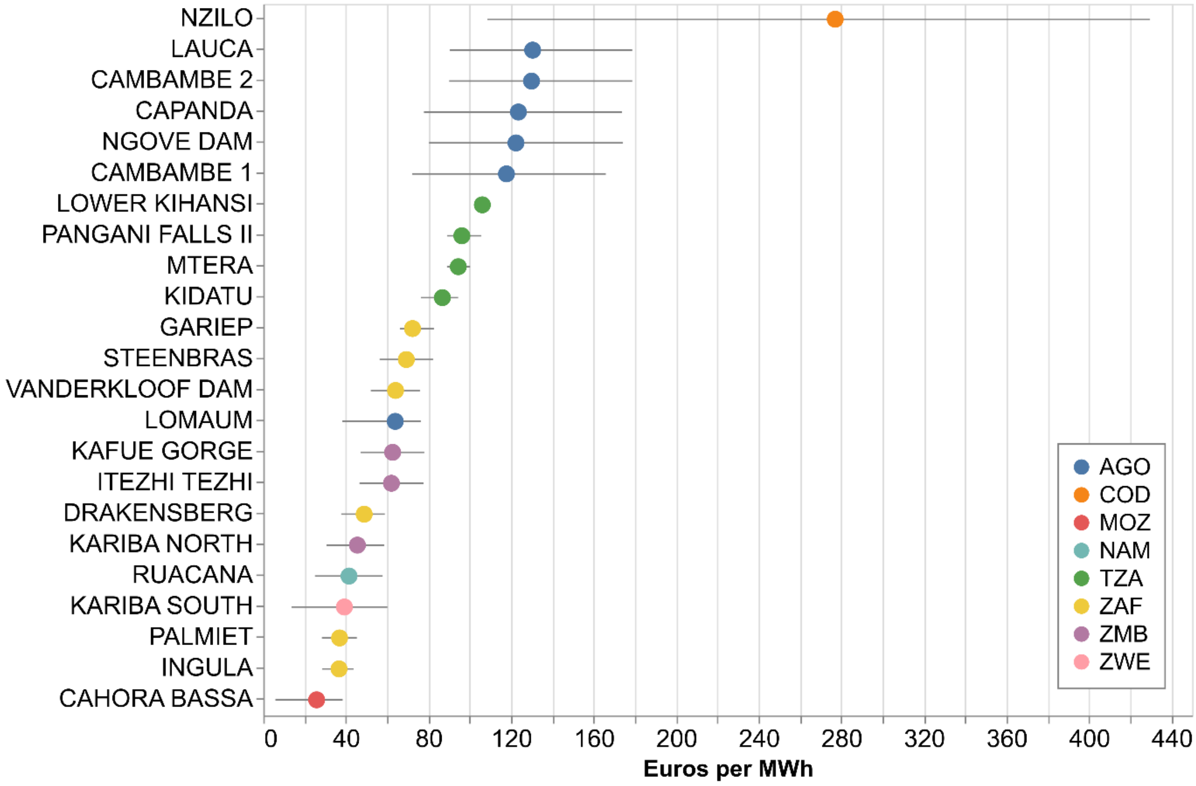
Figure 11: Average annual electricity prices, unserved energy and water values for the range of climatic years in relation to share of annual hydro generation in demand.



Source: JRC, 2020

This can be seen further from Figure 12 where the break-down of water values of individual reservoirs in the SAPP is provided. In this figure generally those reservoirs account for the highest water values that are situated in countries with high electricity price levels in the modelling results such as Angola, Democratic Republic of Congo or Tanzania. This is further modulated by reservoir storage sizes, such that reservoirs with larger storage sizes exhibiting greater flexibility tend to come across with comparatively lower water values.

Figure 12: Averages and bandwidth of yearly average water values of hydro reservoirs over range of climatic years.



Source: JRC, 2020

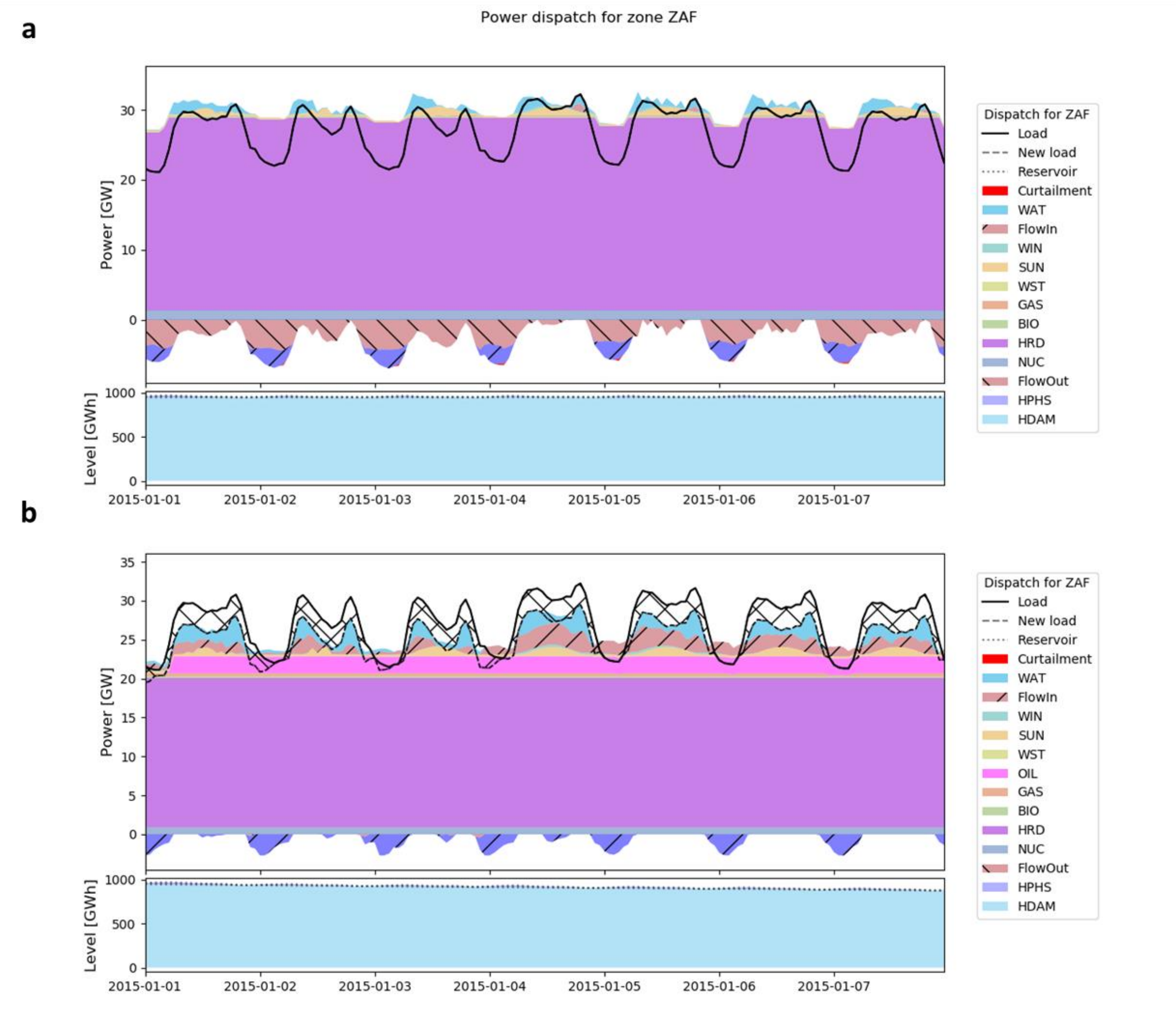
Values for clusters are not displayed.

4 Results of comparing the sensitivity variants to the reference scenario

4.1 Power plant dispatch in South Africa

Figure 13 shows the power dispatch in South Africa for climatic year ‘2016’ in the first week of January, i.e. falling into the period of increased outages of the coal fleet. In the reference case shown in panel a, all load can be served and in periods of lower demand the coal fleet is ramped down. Electricity is both exported and imported, but net exports are positive due to the sufficiently available capacity. The reservoir levels remain untouched. By comparison panel b shows the same period during the outage scenario. Here the maximum output of the coal fleet is reduced by about 8 GW which triggers further changes in the generation patterns. As a consequence no exports take place anymore and as well as well as hydro generation are ramped up which leads to a quick emptying of the reservoir levels. This is however not sufficient to serve all of the load so that during peak demand significant volumes have to be shed.

Figure 13: Power dispatch in South Africa in first week of January in climatic year ‘2016’.



Source: JRC, 2020

Panel a shows reference scenario, panel b shows outage scenario.

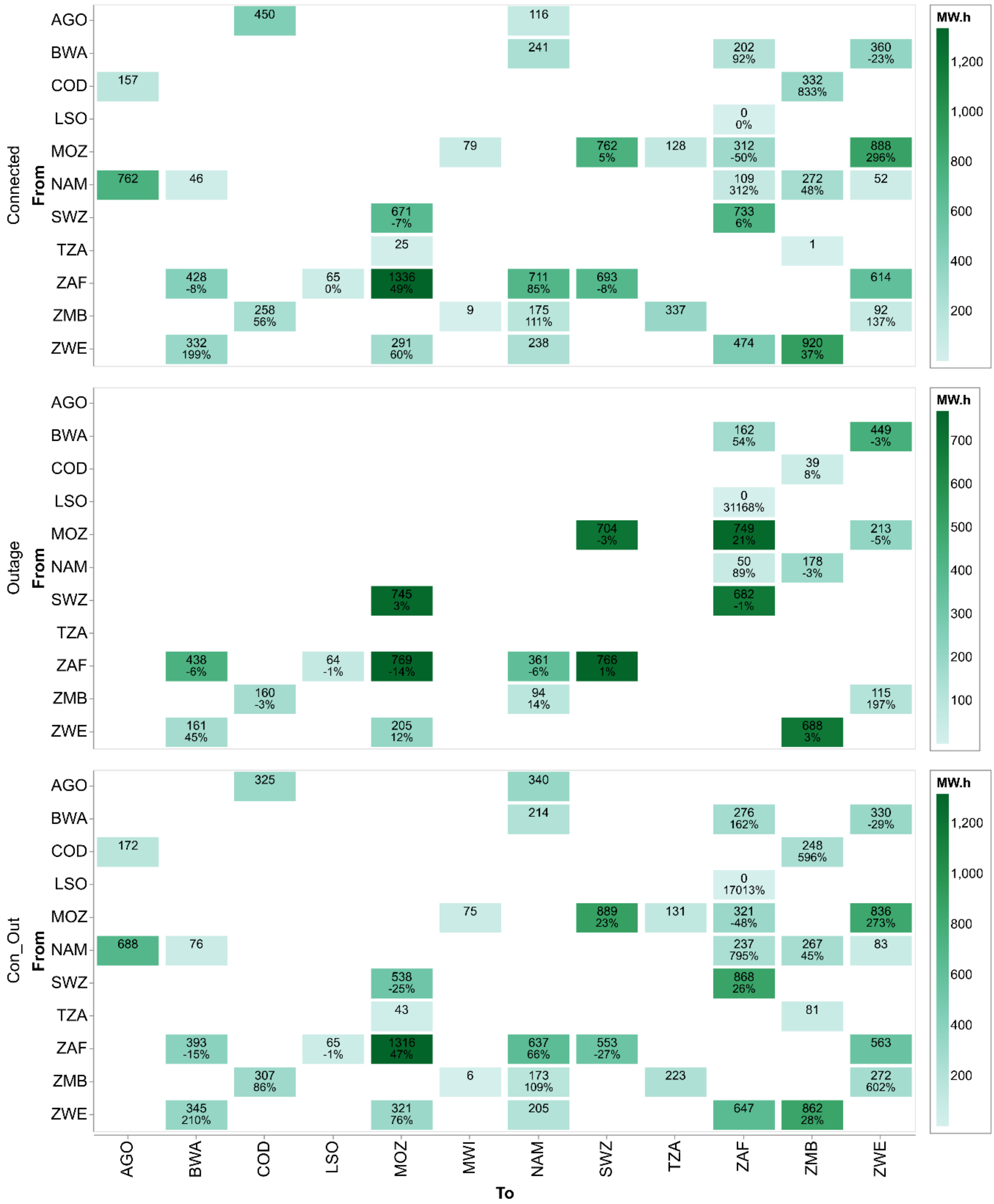
This shows the consequences a vulnerability of the South African coal fleet can have both domestically and in the other SAPP countries through hampered exports. The following sections reveal further consequences of these changed generation patterns.

4.2 Comparison of electricity exchanges

Figure 14 shows the average flows between the SAPP countries in the three sensitivity variants. In each cell the top value refers to the average flow value corresponding to the colour coding, and the bottom value displays the percentage change in comparison to the reference case; where the bottom value is missing the concerned line was not existent in the reference case. Some general observations can be made from this figure. It can be seen that in the two connected cases the average maximum flows are higher than in the outage case with the reference Net Transfer Capacities (NTCs) (1 200 MWh vs. 700 MWh) as indicated by the different scales of the legends. This goes along with overall higher exchanges seen by – in some cases substantially - increased flows on most of the lines. However, on some lines flows are also lowered, for instance in the Connected case on the MOZ-ZAF link by about 50%. This however does not imply in general a lower electricity exchange between these two countries, but rather indicates an increased flexibility to take multiple paths in the electricity network; for instance in this particular case through increased exports from Mozambique to Zimbabwe (MOZ->ZWE) and from there through the new link between Zimbabwe and South Africa (ZWE->ZAF). In this scenario new links also allow to pool resources with countries previously not connected such as the exchanges of Angola with the Democratic Republic of Congo and Namibia.

In the outage scenario, as could be assumed, an increase of exports to South Africa through lines hardly used in the reference case can be observed to help balance the generation deficit caused by reduced output of the thermal fleet. In the Con_Out scenario both patterns are superimposed, i.e., exports to South Africa can be increased over certain lines compared to the Outage scenario while flexibility gained from additional lines can help to cover-up lower exports from South Africa in the first months of the year.

Figure 14: Average flow in MWh (upper number and colour coding) over interconnectors in the three sensitivity scenarios, percentage change to reference scenario (bottom number).

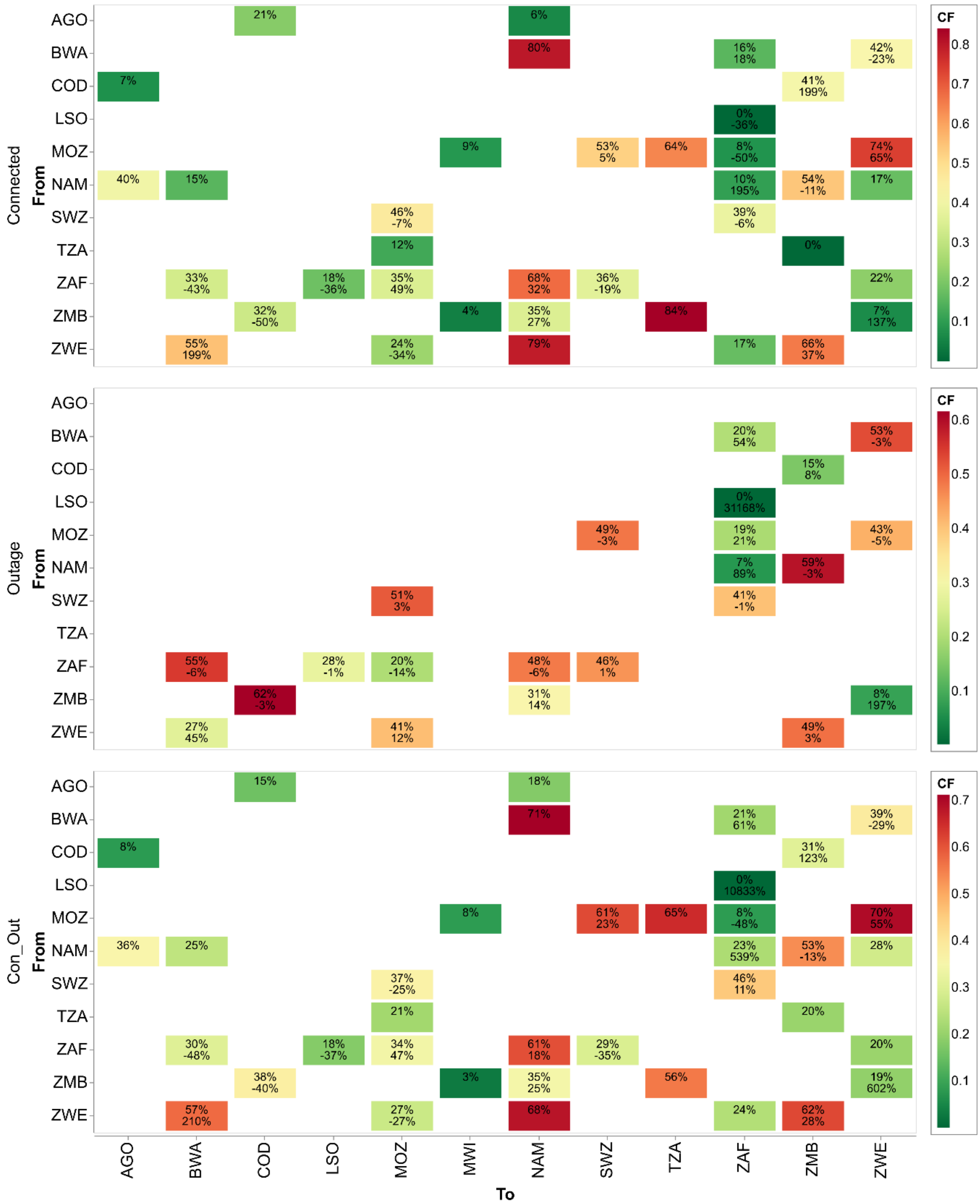


Source: JRC, 2020

Please note different scales legend scales. High value for LSO→ZAF link is due to small reference value.

Figure 15 shows the average capacity factors over all climatic years resulting from the flows in the three sensitivity scenarios. A general pattern that can be observed from these graphs is that in the two scenarios with higher NTCs also the capacity factors are higher, indicated by the scales of the colour legends on the right. This emphasises again that the interconnection capacities added in the two Connected scenarios actually increase trade in average throughout the network. However, as could already be seen for the case of average flows above also the impact on changes in capacity factors of individual lines can be diverging. This is in so far of interest a relatively high capacity utilisation throughout the scenarios provides a more robust indication on the potential benefits of increasing or respectively adding new interconnection capacities. For instance it can be seen that the lines connecting South Africa to Namibia (ZAF→NAM) or Mozambique to Zimbabwe (MOZ→ZWE) belong in all three scenarios, an as well in the reference case, to the group with a comparatively high capacity utilisation. In addition, new interconnections not present in the reference case, such as those between Botswana and Namibia (BWA→NAM) or Zambia and Tanzania (ZMB→TZA) are among those with the highest capacity utilisation. In general, those projects with high capacity factors can be considered promising candidate projects for new interconnection capacity additions or expansions respectively that can be assessed further in more detailed analyses.

Figure 15: Average capacity factors (top number and colour coding) of interconnectors resulting from flows, and percentage change to reference scenario (bottom number).



Source: JRC, 2020

Please note different scales legend scales. High value for LSO->ZAF link is due to small reference value.

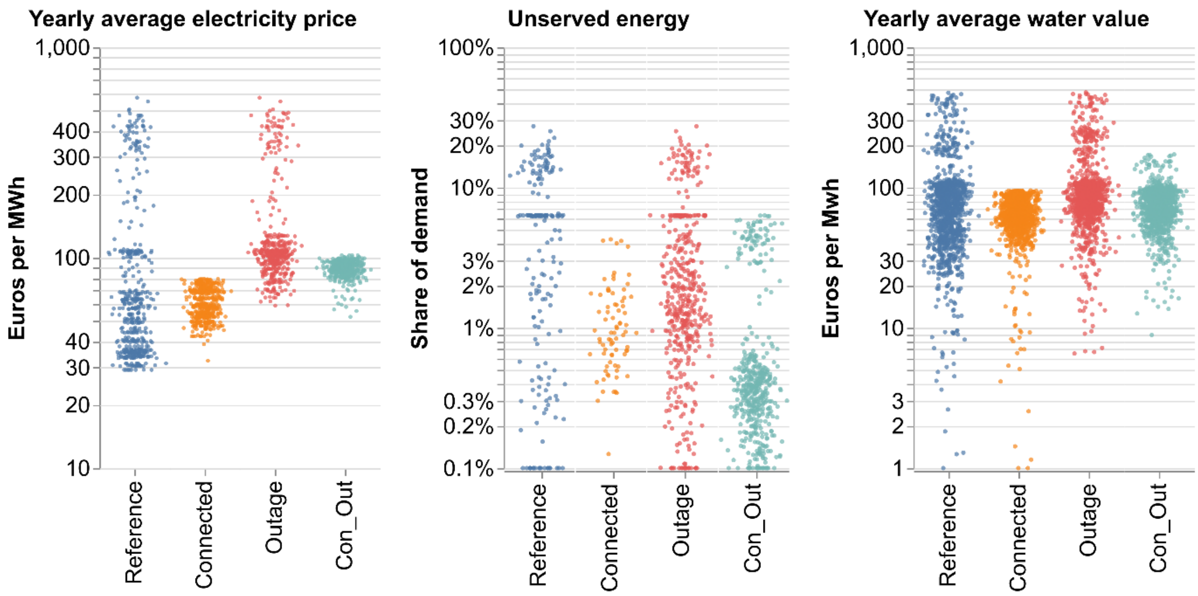
4.3 Selected impacts on techno-economic performance

Figure 16 compares selected techno-economic indicators for the four scenarios. The panel on the left shows the range of yearly average electricity prices. The reference scenario exhibits the biggest range of price levels comprising both the lowest and highest levels of around 30 Euros per MWh and almost 600 Euros per MWh respectively. The majority of price levels can however be found in the 30 to 110 Euros per MWh range. Additional interconnection capacities in the Connected Scenario facilitate pooling of resources and price convergence – as a consequence the range of price levels is substantially narrowed. This raises the lower-end price levels by about 10 to 40 Euros per MWh, the top-end range of price levels however is lowered to about 80 Euros per MWh. In the Outage scenario in the countries not connected similar price spikes up to almost 600 Euros per MWh occur, however due to the increased outage at the beginning of the year the low-end of average price levels is significantly lifted to about 60 Euros per MWh. In the Con_Out scenario price levels converge again, which however does not lift the lower-end price levels above the Outage scenario, rather a slight decrease can be observed. This illustrates the ability of higher interconnection capacities in the SAPP not only to facilitate price convergence but also resilience against economic consequences of supply interruptions.

The middle panel shows the unserved energy (load curtailment and shedding) as share of demand. Again in the Reference and Outage scenarios a much higher range can be observed, caused in particular by the situation in the non-connected countries. At first glance the patterns in both these scenarios look very much alike, it has however to be noted that for the Outage scenario a significantly higher occurrence of strips is displayed revealing a higher frequency of such events in this scenario. The two scenarios with higher connections capacities significantly reduce the top-end values of unserved energy shares from about 30% to about 4%, respectively 6% (note the logarithmic scale). In comparison between the Connected and the Con_Out scenarios a significantly higher frequency of unserved energy events can be ascertained for the latter.

The panel on the right displays the yearly average water values of all the reservoirs that have been modelled. As already seen in the discussion of the results for the reference case the linkage to the electricity prices becomes evident, whereas at the same time the somewhat wider distribution accounts for the heterogeneity in terms of revoir specific attributes. However, given that the bulk of water values in each scenario coherently can be found in the range between about 40 and 110 Euros per MWh also indicates some sort of robustness of the water values against parameter variations which can possibly be deducted from the reservoirs' ability to flexibly allocate their generation over time.

Figure 16: Stripplot comparing selected techno—economic indicators across countries and climatic years for the four scenarios.

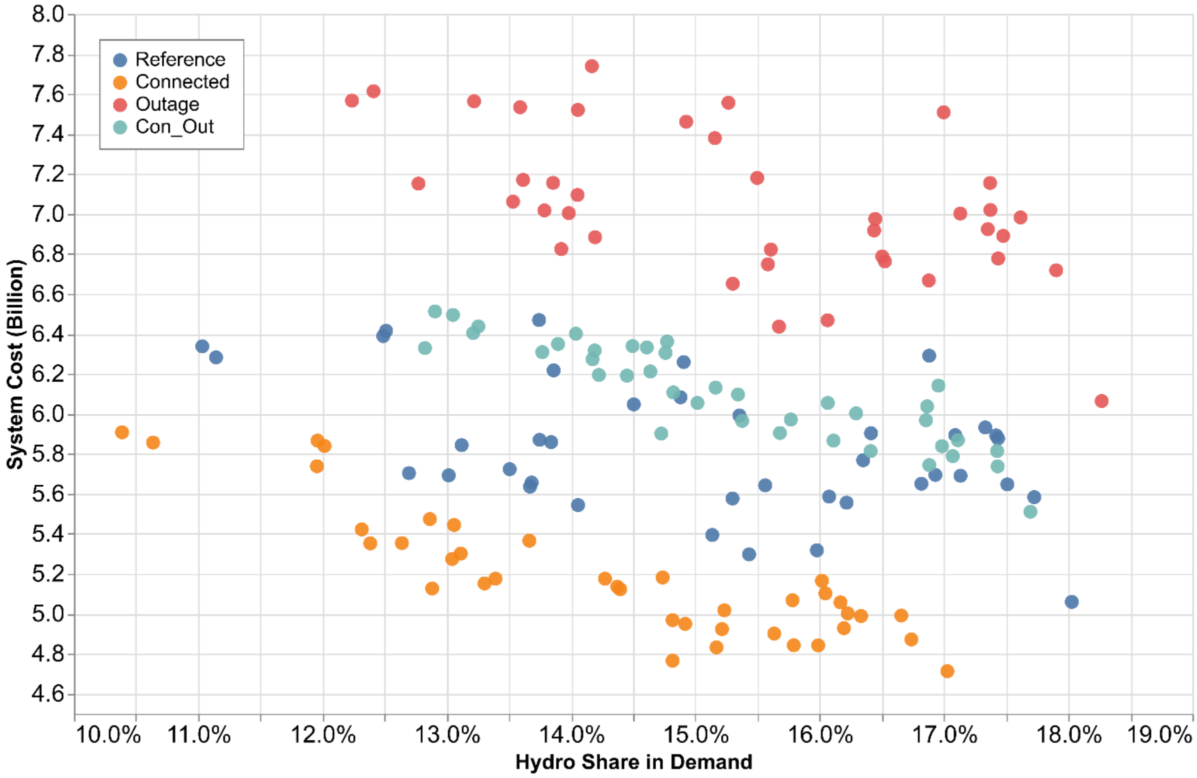


Source: JRC, 2020

Please note the logarithmic scales of the axes.

All the results discussed in this section affect the economic costs of operating the SAPP power system. To conclude this section Figure 17 compares the yearly system costs for all climatic yeas for the four scenarios. From horizontal axis, which shows the share of hydro generation in the SAPP system demand, it can be seen that this share ranges between 10% and 18%. Moreover, the data points show that higher shares of hydro generation go along with reduced system costs and the rate of reduction seems to be relatively similar across scenarios. Roughly speaking, for each scenario the difference in system costs between the lowest and highest shares of hydro generation can be estimated at one billion Euros per year, which translated into a significant improvement in the order of 10% to 20%. For the Outage scenario with the highest share of hydro generation the improvement is even significantly better which underlines the importance hydro availability can play for generation adequacy and thus economic performance. Moreover, Figure 17 reveals substantial differences in the absolute ranges of system costs across the scenarios. The differences between the Connected and Reference scenarios can be found in an almost comparable order of magnitude of one billion Euros per year as the variation over the share of hydro generation. The difference between the Con_Out and Outage scenarios of up to two billion Euros per year presents even higher which emphasizes again that in addition to lowering the cost of generation through pooling resources high interconnectivity also contributes to higher resilience against the economic consequences of supply disruptions.

Figure 17: Comparison of system costs in each climatic year in relation to hydro generation share in demand for the four scenarios.



Source: JRC, 2020

5 Discussion and conclusions

The countries in the SAPP, albeit heterogeneous in terms of their economic development including the maturity of their energy systems, face the joint challenge of having to expand and transform their electricity infrastructure. This is on the one hand driven by the need to serve demand that is expected to grow sharply in order to provide for electricity access, and to keep up with projected population growth and economic convergence. In particular the Democratic Republic of Congo, Malawi and Mozambique are countries with low GDP per capita and low energy access rates that can be expected to contribute to future rising demand. On the other hand changing climatic conditions have immediate implications for the electricity generation in the SAPP. A large share of countries (Angola, Democratic Republic of Congo, Lesotho, Mozambique, Malawi and Zambia) rely on hydropower as their primary generation option and already today major rivers, such as the Zambezi or the Congo, feeding the water storage reservoirs in the region, are subject to significant variability of their mean annual discharge. This variability, which is particularly high in the fall season, has been confirmed through the analyses carried out for this report where the discharge variability of 39 climatic years has been analysed for all larger hydro power plants (>50 MW) in the SAPP. In recent years below-average discharge levels have caused electricity supply interruptions in many of the SAPP countries (see Box 1) and it can be assumed that climate change could exacerbate such a tendency. In conjunction with the changing climate also the occurrence of extreme events, such as the floods in South Africa, which reduced the operation of the coal fleet with impacts on several SAPP countries, has to be considered. These dimensions have to be taken into account when assessing the challenges and opportunities of operating and developing the power system in the SAPP in the context of the water-power nexus.

Recognising that addressing all these aspects is beyond the scope of this work, the main contributions of this report focus on the following three objectives:

— First, to provide a knowledge base for analysing and understanding implications of climate-driven water availability for the power system operation and planning in the SAPP. To achieve this we have compiled, cross-validated and analysed a large amount of relevant datasets as well as the pertinent literature. Based on these data we calibrated the open-source power dispatch model Dispa-SET to the situation that has been characteristic for the SAPP in 2016/2017. This allowed us to validate and better understand the current situation in the SAPP that is characterised by an insufficient availability of generation capacity – caused by a lack of installed capacity in some countries, technical outages and variable availability of hydropower - to consistently meet increasing electricity demand. This situation is in general more pronounced in those SAPP member countries that are not yet connected to the interconnected electricity network, namely Angola, Malawi and Tanzania, whereas in the Democratic Republic of Congo the deficit of generation adequacy is most severe. This is reflected in increased levels of unserved energy that differ by country, but in our simulations can reach up to 25% of yearly demand in Malawi. The simulations of the climatic conditions experienced in the SAPP over a large range of historic climatic years also reveal that a higher availability of water can substantially alleviate the negative economic consequences of unserved electricity on electricity price levels and hampered economic activity (not quantified in this study).

— Second, the datasets, modelling tools and insights derived from the situation that has been characteristic for the SAPP in 2016/2017 provide a suitable reference case against which hypothesis through sensitivity analyses can be tested or upon which future policy scenarios can be developed. Future work with this framework serving the needs of policy partners could put a more granular focus on specific assets, e.g. valuation of specific power plants or interconnection projects, or look at the benefits of pan-Africa or Africa-EU cooperation, e.g. by linking different pools and power systems. To facilitate work at this end we make all the relevant files accessible open source through the JRC Data Catalogue under the WEFE collection[8].

— Third, in terms of policy-relevant questions two themes that have been shown to be of critical relevance in framing the analysis of the SAPP are explored further in this report through dedicated sensitivity analyses. These are the impacts of realising increased inter-connections between the SAPP countries, by implementing all currently considered candidate projects and the consequences of supply interruptions in South Africa both within the country and for the other SAPP countries. Our results show that capacity shortage in South Africa would negatively spill-over to other SAPP countries in terms of increased levels of unserved energy and electricity prices. Contrary, an increased interconnectedness of the SAPP power system allows the currently unconnected countries to participate in the gains of pooling resources and overall, by providing more flexible paths for the electricity to flow, increases the resilience against

[8] https://data.jrc.ec.europa.eu/collection/id-00134

electricity supply interruptions. By comparing the capacity factors of interconnectors for a broad range of hydro-climatic conditions, we identify promising candidate projects for new interconnection capacity additions or expansions respectively that can be assessed further in more detailed analyses. In terms of socio-economic impacts increased interconnectedness is reflected in an overall significantly reduced and smoothed distribution of electricity price and unserved electricity levels. A comparison of total system costs for the whole SAPP across the climatic years in the four scenarios also reveals that these can differ by about 20% depending on how much water is available for hydro generation. A similar order of cost reduction can be achieved through a better interconnection of the SAPP countries which places an emphasis on grid expansion policies as only the latter one can be (directly) controlled through policy decisions.

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List of abbreviations and definitions

AGO	Angola
BWA	Botswana
CAPP	Central African Power Pool
DRC	Democratic Republic of Congo
EAPP	Eastern African Power Pool
HDAM	Hydro Dam
HPHS	Hydro Pumped Storage
HROR	Hydro Run-of-River
LSO	Lesotho
MILP	Mixed-integer linear programming
MWI	Malawi
MOZ	Mozambique
MTS	Mid-term Hydro-Thermal Scheduling
NAM	Namibia
NTC	Net Transfer Capacity
JRC	Joint Research Centre
NAPP	North African Power Pool
SADC	Southern African Development Community
SAPP	Southern Africa Power Pool
SSA	Sub-Saharan Africa
SWZ	Swaziland (Eswatini)
TEMBA	The Electricity Model Base for Africa
TZA	Tanzania
UCM	Unit Commitment Model
UNECA	United Nations Economic Commission for Africa
WAPP	West African Power Pool
WEFE	Water Energy Food and Ecosystem
ZAF	South Africa
ZMB	Zambia
ZWE	Zimbabwe

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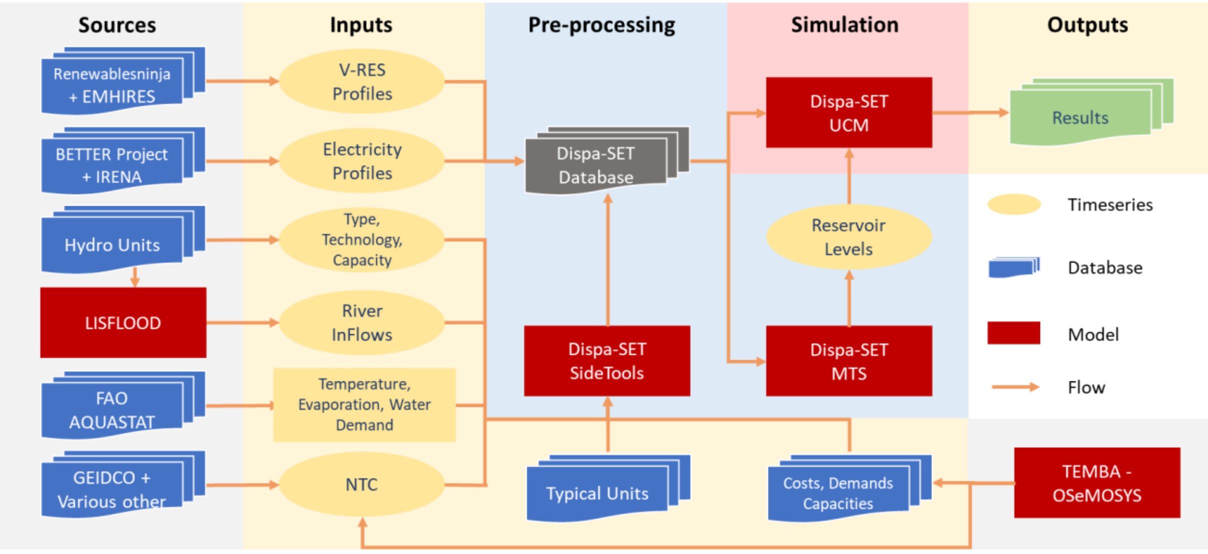
Annexes

Annex 1. Description of modelling workflow and tools

The modelling workflow consists of the five elements illustrated in Figure 18. The usual measured historical or simulated input data, such as hourly time series, is complemented with the TEMBA Reference scenario outputs. These inputs include costs, demand projections and capacities (aggregated only per fuel type) as well as some NTC values. It also provides yearly energy generation from which time series are generated for unit availabilities, demand profiles and energy flow limits between zones. High emphasis is put on the pre-processing of the input data. The framework consists of four models, LISFLOOD is used for generation of multiannual hydro profiles, TEMBA is used for long term generation expansion planning, third is the transitioning model between the LISFLOOD and TEMBA outputs formatted into the Dispa-SET readable format while the fourth and final one is the Dispa-SET mid-term scheduling module used for pre-allocation of large storage units such as HDAM and pumped storage units (HPHS). Reservoir levels computed by the Dispa-SET MTS module are then used as minimum level constraints in the main Dispa-SET unit commitment (UCM) mode.

Figure 18: Relational block-diagram between models and various data sources used within this study.



Source: (Pavicevic and Quoilin, 2020)

TEMBA - OSeMOSYS inputs are complemented with historical (where applicable) and computed hourly timeseries profiles. Unit commitment and power dispatch is solved with Dispa-SET.

In the following a brief description of each modelling tool is provided.

LISFLOOD

Lisflood is a rainfall-runoff hydrological model capable of simulating the hydrological processes that occur in a particular catchment area. It was developed by the Joint Research Centre (JRC) of the European Commission, with the specific objective to produce a tool that can be used in large and trans-national catchments for a variety of applications, including: flood forecasting, assessing the effects of river regulation measures, the effects of land-use change and the effects of climate change. Within this study, LISFLOOD was used as a simulation tool for predicting historical discharge rates in river basins on which hydro units are located.

TEMBA – OSeMOSYS

The Electricity Model Base for Africa (TEMBA) was initially developed with the United Nations Economic Commission for Africa (UNECA) to provide a foundation for the analysis of the continental-scale African energy system. For the purpose of this analysis, the results from the TEMBA model are used as inputs for assessing the future scenario in the three African power pools. The input data and modelling framework used within the TEMBA - OSeMOSYS model are described in more detail by Pappis et al. (Pappis et al., 2019). Main outputs of the study are as follows: capacity data (as investment in energy supply in Africa has been growing), cost and performance data, fuel price projections, new energy demand projections.

Dispa-SET

The Dispa-SET model is an open-source unit commitment and optimal dispatch model focused on the balancing and flexibility problems in smart energy systems with high shares of VRES. It is mainly developed within the JRC of the European Commission and in close collaboration with the University of Liège and the KU Leuven. The core formulation of the model is an efficient Mixed-integer linear programming (MILP) formulation of the Unit Commitment Model (UCM) problem. As mentioned before, a simplified hydro-thermal allocation (MTS), is a linear programming approximation (i.e. integer variables are relaxed) of the UCM modelling approach, used to pre-allocate reservoir levels of seasonal storage units. The main purpose of using the Dispa-SET model is the possibility of analysing large interconnected power systems with a high level of detail. Dispa-SET is the main modelling framework used within this study. The demands are assumed to be inelastic to the price signal. The MILP objective function is, therefore, the total generation cost over the optimization period and can be summarized in the following equation:

$$\mathrm{Min}\, TotalSystemCost = \sum_{\forall u,i} \left(\begin{array}{c} CostStartUp_{i,u} + CostShutDown_{i,u} + \\ CostFixed_u \cdot Committed_{i,u} + \\ CostVariable_{i,u} \cdot Power_{i,u} + \\ CostRampUp_{i,u} + CostRampDown_{i,u} + \\ PriceTransmission_{i,l} \cdot Flow_{i,l} + \\ \sum_n \left(CostLoadShedding_{i,n} \cdot ShedLoad_{i,n} \right) + \\ VOLL_{Power} \cdot \left(LL_{MaxPower,i,n} + LL_{MinPower,i,n} \right) + \\ VOLL_{Reserve} \cdot \left(LL_{2U,i,n} + LL_{2D,i,n} + LL_{3U,i,n} \right) + \\ VOLL_{Ramp} \cdot \left(LL_{RampUp,u,i} + LL_{RampDown,u,i} \right) \end{array} \right) \tag{1}$$

The main constraint to be met is the power supply-demand balance, for each period and each zone, in the day-ahead market as proposed in the following equation:

$$\begin{aligned} \sum_u \left(\mathrm{Power}_{u,i} \cdot Location_{u,n} \right) + \sum_l \left(\mathrm{Flow}_{l,i} \cdot LineNode_{l,n} \right) = Demand_{DA,n,h} \\ + \sum_r \left(\mathrm{StorageInput}_{s,h} \cdot Location_{s,n} \right) - ShedLoad_{n,i} - LL_{MaxPower_{n,i}} \\ + LL_{MinPower_{n,i}} \end{aligned} \tag{2}$$

According to this restriction, the sum of the power generated by all the units present in the node (including the power generated by the storage units), the power injected from neighbouring nodes, and the curtailed power from intermittent sources is equal to the day ahead load in that node.

Annex 2. Additional input parameters

Table 3: Cooling technologies and water withdrawal and consumption factors of the SAPP power plan fleet.

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
COD_BIO_STUR_cluster	Tower	3.32	2.09
MOZ_BIO_STUR_cluster	Tower	3.32	2.09
MWI_BIO_STUR_cluster	Tower	3.32	2.09
SWZ_BIO_STUR_cluster	Tower	3.32	2.09
TZA_BIO_STUR_cluster	Tower	3.32	2.09
ZAF_BIO_ICEN_cluster	Tower	3.32	2.09
ZAF_BIO_STUR_cluster	Tower	3.32	2.09
ZMB_BIO_STUR_cluster	Tower	3.32	2.09
ZWE_BIO_STUR_cluster	Tower	3.32	2.09
MOZ_GAS_ICEN_GIGAWATT PARK	Dry	0.00	0.00
ZAF_GAS_GTUR_SECUNDA	Once-through	137.58	0.95
TZA_GAS_GTUR_UBUNGO SONGAS	Dry	0.00	0.00
ZAF_GAS_ICEN_SASOL ONE	Tower	2.22	1.81
TZA_GAS_GTUR_KINYEREZI	Dry	0.00	0.00
MOZ_GAS_ICEN_RESSANO GARCIA	Dry	0.00	0.00
ZAF_GAS_STUR_MOSSEL BAY	Tower	4.55	3.13
AGO_GAS_GTUR_SOYO LNG PLANT	Dry	0.00	0.00
MOZ_GAS_ICEN_GIGAWATT PARK-3	Dry	0.00	0.00
TZA_GAS_GTUR_SYMBION UBUNGO	Dry	0.00	0.00
TZA_GAS_ICEN_UBUNGO NEW	Dry	0.00	0.00
TZA_GAS_GTUR_UBUNGO-II	Dry	0.00	0.00
AGO_GAS_GTUR_FUTILA	Dry	0.00	0.00
MOZ_GAS_GTUR_MAPUTO	Dry	0.10	0.10
AGO_GAS_GTUR_cluster	Dry	0.01	0.01
COD_GAS_ICEN_cluster	Dry	0.01	0.01

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
MOZ_GAS_GTUR_cluster	Dry	0.01	0.01
MOZ_GAS_ICEN_cluster	Dry	0.01	0.01
TZA_GAS_ICEN_cluster	Dry	0.01	0.01
ZAF_GAS_COMC_cluster	Dry	0.01	0.01
ZAF_GAS_GTUR_cluster	Dry	0.01	0.01
ZAF_GAS_ICEN_cluster	Dry	0.01	0.01
ZAF_HRD_STUR_MAJUBA	Dry	0.33	0.22
ZAF_HRD_STUR_KENDAL	Tower	2.22	1.81
ZAF_HRD_STUR_MATIMBA	Dry	0.33	0.22
ZAF_HRD_STUR_LETHABO	Tower	2.22	1.81
ZAF_HRD_STUR_TUTUKA	Tower	2.22	1.81
ZAF_HRD_STUR_DUVHA	Tower	2.22	1.81
ZAF_HRD_STUR_MATLA	Tower	2.22	1.81
ZAF_HRD_STUR_KRIEL	Tower	2.22	1.81
ZAF_HRD_STUR_ARNOT	Tower	2.22	1.81
ZAF_HRD_STUR_HENDRINA	Tower	2.22	1.81
ZAF_HRD_STUR_CAMDEN	Tower	2.22	1.81
ZAF_HRD_STUR_MEDUPI	Dry	0.33	0.22
ZAF_HRD_STUR_GROOTVLEI	Tower	2.22	1.81
ZWE_HRD_STUR_HWANGE	Tower	2.22	1.81
ZAF_HRD_STUR_KELVIN	Tower	2.22	1.81
BWA_HRD_STUR_MORUPULE-B	Dry	0.33	0.22
ZAF_HRD_STUR_SECUNDA	Once-through	137.58	0.95
ZAF_HRD_STUR_ROOIWAL	Tower	2.22	1.81
ZAF_HRD_STUR_SASOL ONE	Tower	2.22	1.81
BWA_HRD_STUR_MORUPULE-A	Dry	0.33	0.22
NAM_HRD_STUR_VAN ECK	Dry	0.33	0.22

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
ZWE_HRD_STUR_MUNYATI	Dry	0.33	0.22
ZWE_HRD_STUR_HARARE	Dry	0.33	0.22
ZAF_HRD_STUR_RICHARDS BAY MIL	Tower	2.22	1.81
ZAF_HRD_STUR_BLOEMFONTEIN	Tower	2.22	1.81
ZAF_HRD_STUR_NGODWANA MILL	Tower	4.55	3.13
ZAF_HRD_STUR_SAICCOR MILL	Tower	4.55	3.13
BWA_HRD_STUR_cluster	Tower	2.22	1.81
TZA_HRD_STUR_cluster	Tower	2.22	1.81
ZAF_HRD_STUR_cluster	Tower	2.22	1.81
ZMB_HRD_STUR_cluster	Tower	2.22	1.81
ZAF_NUC_STUR_KOEBERG	Once-through	167.86	1.02
ZAF_OIL_GTUR_GOURIKWA	Dry	0.00	0.00
AGO_OIL_GTUR_CAZENGA	Dry	0.00	0.00
ZAF_OIL_GTUR_ANKERLIG	Dry	0.00	0.00
ZAF_OIL_GTUR_AVON SHAKASKRAAL	Dry	0.00	0.00
ZAF_OIL_GTUR_DEDISA	Dry	0.00	0.00
ZWE_OIL_ICEN_DEMA SUBSTATION	Dry	0.00	0.00
ZAF_OIL_GTUR_ACACIA	Dry	0.00	0.00
ZAF_OIL_GTUR_PORT REX	Once-through	43.07	0.38
AGO_OIL_GTUR_CAMINHOS DE FERR	Dry	0.00	0.00
BWA_OIL_ICEN_FRANCISTOWN APR	Dry	0.00	0.00
TZA_OIL_ICEN_TEGATA	Dry	0.00	0.00
AGO_OIL_GTUR_BARCAZA LUANDA-1	Dry	0.00	0.00
BWA_OIL_GTUR_ORAPA SUBSTATION	Dry	0.00	0.00
TZA_OIL_ICEN_NYAKATO-II	Dry	0.00	0.00
MWI_OIL_ICEN_KAYELEKERA MINE	Dry	0.00	0.00
ZAF_OIL_GTUR_ATHLONE	Tower	2.22	1.81

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
ZAF_OIL_GTUR_ROGGEBAAI	Dry	0.00	0.00
TZA_OIL_ICEN_SYMBION DODOMA	Dry	0.00	0.00
AGO_OIL_GTUR_cluster	Dry	0.00	0.00
AGO_OIL_ICEN_cluster	Dry	0.00	0.00
AGO_OIL_STUR_cluster	Dry	0.00	0.00
BWA_OIL_ICEN_cluster	Dry	0.00	0.00
COD_OIL_ICEN_cluster	Dry	0.00	0.00
LSO_OIL_ICEN_cluster	Dry	0.00	0.00
MOZ_OIL_ICEN_cluster	Dry	0.00	0.00
MWI_OIL_ICEN_cluster	Dry	0.00	0.00
NAM_OIL_ICEN_cluster	Dry	0.00	0.00
NAM_OIL_STUR_cluster	Dry	0.00	0.00
SWZ_OIL_ICEN_cluster	Dry	0.00	0.00
TZA_OIL_GTUR_cluster	Dry	0.00	0.00
TZA_OIL_ICEN_cluster	Dry	0.00	0.00
ZAF_OIL_GTUR_cluster	Dry	0.00	0.00
ZAF_OIL_ICEN_cluster	Dry	0.00	0.00
ZAF_OIL_STUR_cluster	Dry	0.00	0.00
ZMB_OIL_GTUR_cluster	Dry	0.00	0.00
ZMB_OIL_ICEN_cluster	Dry	0.00	0.00
ZMB_OIL_STUR_cluster	Dry	0.00	0.00
ZWE_OIL_ICEN_cluster	Dry	0.00	0.00
ZAF_SUN_PHOT_DE AAR PROJECT-1	Dry	0.00	0.00
ZAF_SUN_STUR_KAXU SOLAR ONE	Dry	0.00	0.00
ZAF_SUN_PHOT_JASPER POWER	Dry	0.00	0.00
ZAF_SUN_PHOT_SISHEN SOLAR	Dry	0.00	0.00
ZAF_SUN_PHOT_MULILO PRIESKA	Dry	0.00	0.00

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
ZAF_SUN_PHOT_PALEISHEUWEL	Dry	0.00	0.00
ZAF_SUN_PHOT_KATHU	Dry	0.00	0.00
ZAF_SUN_PHOT_DREUNBERG SOLAR	Dry	0.00	0.00
ZAF_SUN_PHOT_KALKBULT	Dry	0.00	0.00
ZAF_SUN_PHOT_LESEDI	Dry	0.00	0.00
ZAF_SUN_PHOT_LETSATSI	Dry	0.00	0.00
ZAF_SUN_PHOT_TOM BURKE	Dry	0.00	0.00
ZAF_SUN_PHOT_BOSHOFF SOLAR	Dry	0.00	0.00
ZAF_SUN_STUR_BOKPOORT-1	Tower	3.79	3.79
BWA_SUN_PHOT_cluster	Dry	0.00	0.00
NAM_SUN_PHOT_cluster	Dry	0.00	0.00
ZAF_SUN_PHOT_cluster	Dry	0.00	0.00
ZAF_SUN_STUR_cluster	Dry	0.00	0.00
MOZ_WAT_HDAM_CAHORA BASSA	Dry	5000.04	283.82
AGO_WAT_HDAM_LAUCA	Dry	5000.04	68.89
ZAF_WAT_HPHS_INGULA	Dry	5000.04	84.85
ZMB_WAT_HDAM_KARIBA NORTH	Dry	5000.04	554.67
ZAF_WAT_HPHS_DRAKENSBERG	Dry	5000.04	84.85
AGO_WAT_HDAM_CAMBAMBE-2	Dry	5000.04	68.89
ZMB_WAT_HDAM_KAFUE GORGE	Dry	5000.04	554.67
COD_WAT_HDAM_INGA-II	Dry	0.00	0.00
ZWE_WAT_HDAM_KARIBA SOUTH	Dry	5000.04	1352.56
AGO_WAT_HDAM_CAPANDA	Dry	5000.04	68.89
ZAF_WAT_HPHS_PALMIET	Dry	5000.04	84.85
ZAF_WAT_HDAM_GARIEP	Dry	5000.04	84.85
NAM_WAT_HDAM_RUACANA	Dry	5000.04	283.82
COD_WAT_HDAM_INGA-I	Dry	0.00	0.00

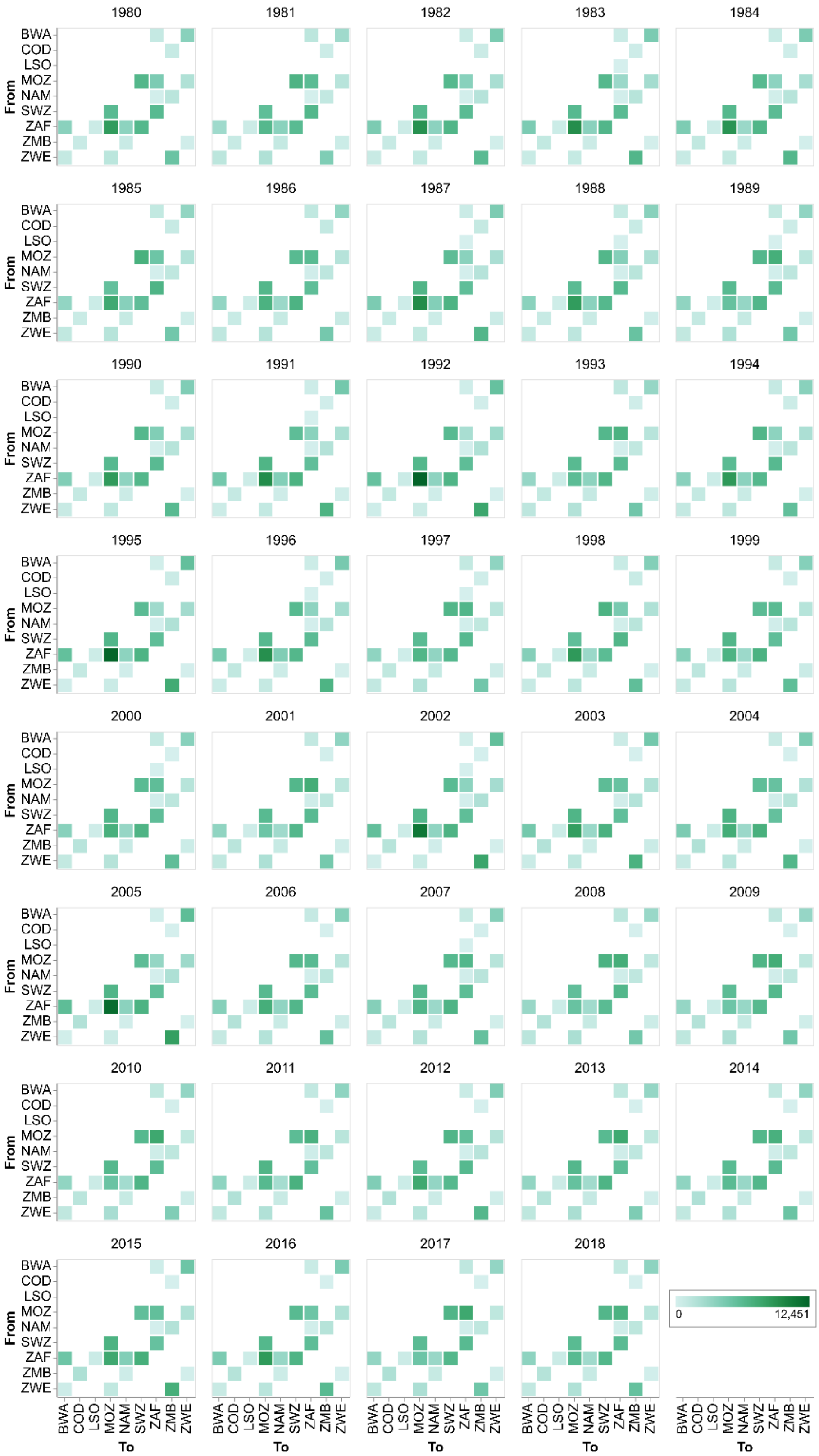
Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
AGO_WAT_HDAM_CAMBAMBE-1	Dry	5000.04	68.89
ZAF_WAT_HDAM_VANDERKLOOF DAM	Dry	5000.04	84.85
TZA_WAT_HDAM_KIDATU	Dry	5000.04	19.13
COD_WAT_HDAM_NSEKE	Dry	0.00	0.00
TZA_WAT_HDAM_LOWER KIHANSI	Dry	5000.04	19.13
ZAF_WAT_HDAM_STEENBRAS	Dry	5000.04	84.85
MWI_WAT_HROR_KAPICHIRA	Dry	0.00	0.00
ZMB_WAT_HDAM_ITEZHI TEZHI	Dry	5000.04	554.67
ZMB_WAT_HROR_VICTORIA FALLS	Dry	0.00	0.00
MWI_WAT_HROR_NKULA-B	Dry	0.00	0.00
COD_WAT_HDAM_Nzilo	Dry	5000.04	133.47
MWI_WAT_HROR_TEDZANI FALLS	Dry	0.00	0.00
TZA_WAT_HDAM_MTERA	Dry	5000.04	426.59
COD_WAT_HROR_ZONGO-I	Dry	0.00	0.00
LSO_WAT_HDAM_MUELA	Dry	0.00	0.00
COD_WAT_HROR_MWADINGUSHA	Dry	0.00	0.00
TZA_WAT_HDAM_PANGANI FALLS-II	Dry	5000.04	426.59
AGO_WAT_HDAM_LOMAUM	Dry	5000.04	68.89
AGO_WAT_HDAM_NGOVE DAM	Dry	5000.04	68.89
MOZ_WAT_HROR_MAVUZI	Dry	0.00	0.00
AGO_WAT_HDAM_cluster	Dry	5000.04	68.89
AGO_WAT_HROR_cluster	Dry	0.00	0.00
COD_WAT_HDAM_cluster	Dry	5000.04	133.47
COD_WAT_HROR_cluster	Dry	0.00	0.00
LSO_WAT_HROR_cluster	Dry	0.00	0.00
MOZ_WAT_HDAM_cluster	Dry	5000.04	283.82
MOZ_WAT_HROR_cluster	Dry	0.00	0.00

Unit	Cooling Technology	Water Withdrawal (m^3 per Mwh_{el})	Water Consumption (m^3 per Mwh_{el})
MWI_WAT_HROR_cluster	Dry	0.00	0.00
SWZ_WAT_HROR_cluster	Dry	0.00	0.00
TZA_WAT_HDAM_cluster	Dry	5000.04	426.59
TZA_WAT_HROR_cluster	Dry	0.00	0.00
ZAF_WAT_HROR_cluster	Dry	0.00	0.00
ZMB_WAT_HDAM_cluster	Dry	5000.04	554.67
ZMB_WAT_HROR_cluster	Dry	0.00	0.00
ZWE_WAT_HROR_cluster	Dry	0.00	0.00
ZAF_WIN_WTON_AMAKHALA EMOYENI	Dry	0.00	0.00
ZAF_WIN_WTON_GOUDA WIND	Dry	0.00	0.00
ZAF_WIN_WTON_JEFFREYS BAY	Dry	0.00	0.00
ZAF_WIN_WTON_DORPER	Dry	0.00	0.00
ZAF_WIN_WTON_SERE	Dry	0.00	0.00
ZAF_WIN_WTON_WEST COAST ONE	Dry	0.00	0.00
ZAF_WIN_WTON_TSITSIKAMMA	Dry	0.00	0.00
ZAF_WIN_WTON_NOUPOORT	Dry	0.00	0.00
ZAF_WIN_WTON_KOUGA WIND	Dry	0.00	0.00
ZAF_WIN_WTON_NOBELSFONTAINE	Dry	0.00	0.00
ZAF_WIN_WTON_HOPEFIELD WIND	Dry	0.00	0.00
ZAF_WIN_WTON_GRASSRIDGE	Dry	0.00	0.00
ZAF_WIN_WTON_cluster	Dry	0.00	0.00
ZAF_WST_ICEN_cluster	Dry	1.70	0.13
ZAF_WST_STUR_cluster	Dry	1.70	0.13

Source: JRC, 2020

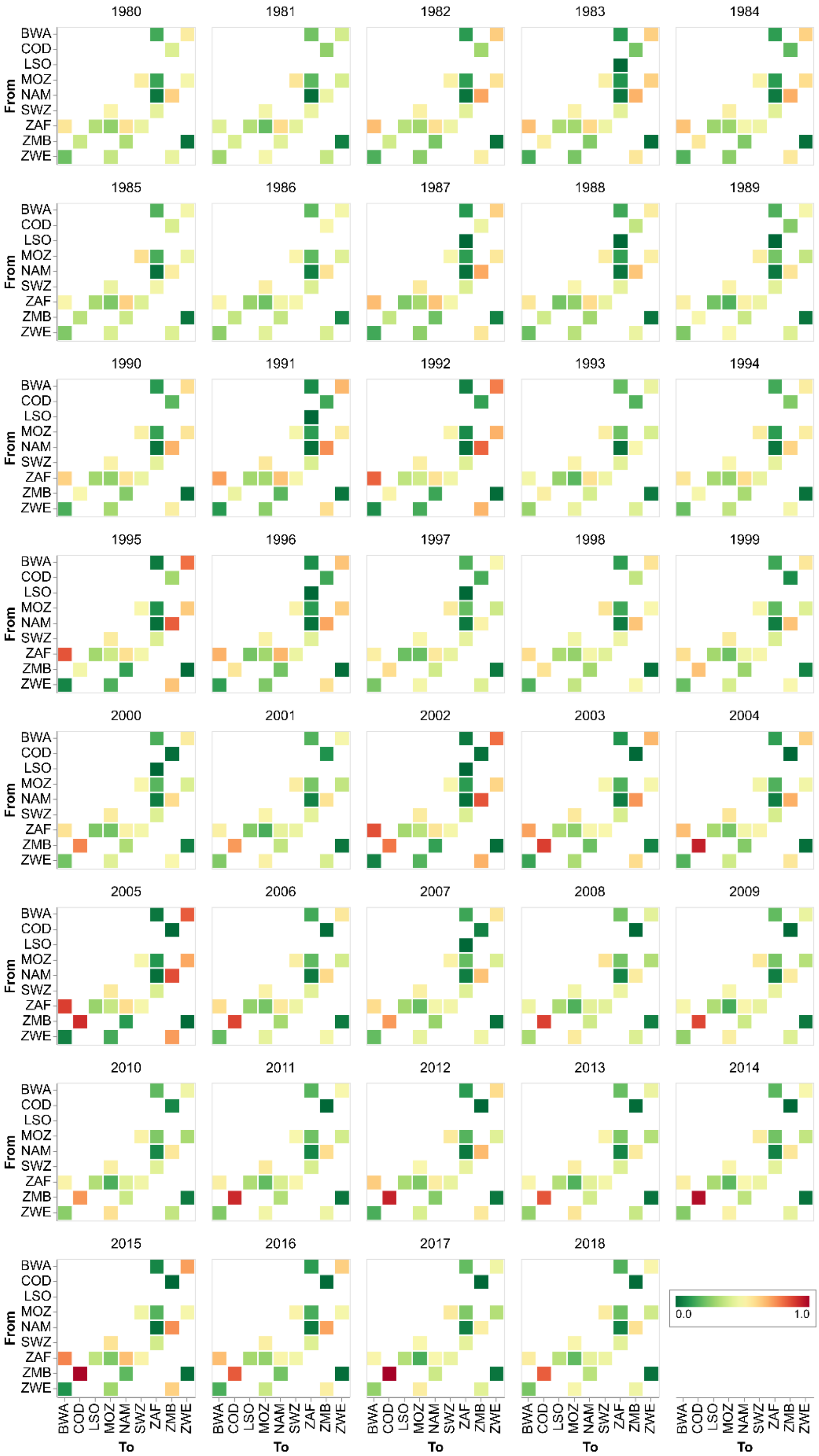
Annex 3. Additional results

Figure 19: Average flow in MWh over interconnectors in the reference case for all climatic years.



Source: JRC, 2020

Figure 20: Average capacity factor of interconnectors in the reference case for all climatic years.



Source: JRC, 2020

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