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# Southern Africa's Water–Energy Nexus: Towards Regional Integration and Development

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**Abstract:** The Southern African Development Community's (SADC) water and energy sectors are under increasing pressure due to population growth and agricultural and industrial development. Climate change is also negatively impacting on the region's water and energy resources. As the majority of SADC's population lives in poverty, regional development and integration are underpinned by water and energy security as the watercourses in the region are transboundary in nature. This paper reviews the region's water and energy resources and recommends policies based on the water–energy nexus approach. This is achieved by reviewing literature on water and energy resources as well as policy issues. Water resources governance provides a strong case to create a water–energy nexus platform to support regional planning and integration as SADC countries share similar climatic and hydrological conditions. However, there has been a gap between water and energy sector planning in terms of policy alignment and technical convergence. These challenges hinder national policies on delivering economic and social development goals, as well as constraining the regional goal of greater integration. Regional objectives on sustainable energy and access to clean water for all can only be achieved through the recognition of the water–energy nexus, championed in an integrated and sustainable manner. A coordinated regional water–energy nexus approach stimulates economic growth, alleviates poverty and reduces high unemployment rates. The shared nature of water and energy resources requires far more transboundary water–energy nexus studies to be done in the context of regional integration and policy formulation.

**Keywords:** policy alignment; sustainable development; technical and policy convergence; regional integration; water–energy nexus

## 1. Introduction

The water–energy nexus describes the inextricable linkages between water and energy [1–3]. Energy production requires water, either directly (hydropower) or indirectly [4,5]. In conventional thermal power plants, the production chain of energy involves various stages including fuel acquisition, processing and transportation. For instance, water is required in the mining, washing, beneficiation and transportation of coal, plant construction and power generation (cooling coal plants). The extraction, treatment (including recycling) and distribution of water also requires energy [2,3]. As such, efforts to develop and/or increase power generation should equally be matched by considerations of water use and/or the water footprint associated with power generation. Energy generation planning should therefore consider water resources and water use [3]; the opposite is true for water extraction, treatment and distribution. However, in reality, water availability is often taken for granted [3] due to the "relative importance" of energy to economic development. In addition, *"energy, water, and environmental sustainability are closely interrelated and are vital not only to the economy but to the health and welfare of all humans"* [3]. Furthermore, projected population growth, climate change and variability and urbanization increasingly call for an integrated approach [6]. These processes reaffirm Schnoor's [7] assertion that the water–energy nexus would become more important in the coming years.

Besides the intrinsic interconnection between water and energy, it is also important to note the negative impacts of energy resources on water quality. The potential of contamination of water by energy resources includes tailings seepage, fracturing fluids and flow-back of oil and gas, seepage and acid mine drainage in coal mining areas affecting both surface and ground water sources. Also, large quantities of wastewater that are produced by biofuels end up polluting water resources. However, these challenges further cement the water–energy nexus as the adoption and implementation of good policies at regional level will go a long way in preserving these resources for sustainable development.

A literature review from energy and water related journals showed that most of the studies describing the water–energy nexus were from developed countries with limited examples from developing and emerging countries. Only papers focusing on the water–energy nexus and water and energy resources were selected. Out of a total of 26 papers that were reviewed for this paper, only eight (8) were from developing countries, showing that developing countries still lag behind in water–energy nexus related policies. Several developed countries are already taking the initiative to include the water–energy nexus in their planning of developmental projects. These include the United States, China, Spain and Australia [8]. While the literature did not show many studies from developing countries, it is in these countries where the largest gaps in policy between water and energy exist. The countries that have gaps in water and energy policy also face challenges associated with population growth, rapid urbanisation and climate change, challenges that also affect water and energy planning for economic development [9]. As the natural occurrence of water and energy resources is not limited by political boundaries, there has been an increasingly prominent notion that integrated water–energy nexus approaches should be developed not only at the national level, but also at the regional level [8,10]. In this regard, Siddiqi and Anadon [2] reviewed the water–energy nexus for the Middle East and North Africa (MENA) region. They found that there was a need to narrow the policy gap between water and energy planning and emphasised the need for an integrated approach—a water–energy nexus. Previously, regional and national policies were linked to achieving the Millennium Development Goals (MDGs), which expired in September 2015. With the advent of the Sustainable Development Goals (SDGs), the water–energy nexus approach becomes indispensable for regional integration and development as well as achieving the national SDGs targets [11]. It is also expected that future policy will be influenced by the SDGs as Sustainable Development Goals 6, 7, 8 and 9 all have targets related to water–energy nexus planning approach. Therefore, this review seeks to highlight the importance and implications thereof of the water–energy nexus to the region's post-2015 development agenda.

In this review, we focus on the water–energy nexus in southern Africa, with particular emphasis on the Southern African Development Community (SADC), a regional economic body that brings together 15 southern African states. The review focuses on the regional development agenda of the SADC region as almost all the river basins are transboundary in nature. In addition, several SADC states share the same power grid as well as the same transboundary watercourses for their energy generation. For example, the Cahorra Bassa Dam in Mozambique, Kariba Dam which is shared between and Zambia, and Itezhi-Tezhi Dam in west-central Zambia all exist on the Zambezi river system. The former two dams, Cahorra Bassa and Kariba, are used for energy generation with the energy generated being used in Mozambique, Zimbabwe, Zambia and South Africa. The transboundary nature of the river basins means that any changes in water courses that are done in upstream countries will have an impact on multiple water uses in downstream countries. Putting more emphasis on individual national interest in such a set-up without considering the interest of neighbouring countries may result in conflict [12,13]. Table 1 shows the transboundary river basins in the SADC region and the riparian countries.

**Table 1.** Transboundary river basins and the riparian states in the SADC region.

| River Basin | Sharing States |
|---|---|
| Buzi | Mozambique, Zimbabwe |
| Congo | Angola, Democratic Republic of Congo, Tanzania, Zambia |
| Cuvelai | Angola, Namibia |
| Incomati | Mozambique, South Africa, Swaziland |
| Kunene | Angola, Namibia |
| Limpopo | Botswana, Mozambique, South Africa, Zimbabwe |
| Maputo | Mozambique, South Africa, Swaziland |
| Nile | Democratic Republic of Congo, Tanzania |
| Okavango | Angola, Botswana, Namibia |
| Orange | Botswana, Lesotho, Namibia, South Africa |
| Pungwe | Mozambique, Zimbabwe |
| Ruvuma | Malawi, Mozambique, Tanzania |
| Save | Mozambique, Zimbabwe |
| Umbeluzi | Mozambique, Swaziland |
| Zambezi | Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, Zimbabwe |

The objectives of SADC include, among other things, achieving development, peace and security, economic growth and integration, poverty alleviation and improving the standard of living of its people. Water and energy are key to economic growth and development which is inextricably linked to the realisation of these objectives. The region faces challenges to the realisation of these goals. These challenges include declining water resources and an energy deficit [14]; this is set against increasing demand for both water and energy driven by an increasing population. The challenges require that a nexus approach be adopted with regards to water and energy. The understanding and analysis of the water–energy nexus will create opportunities to increase the efficient use of resources, secure sustainable access to water and energy and enhance policy coherence. For example, promoting water efficient energy generation would produce more energy while consuming less water. Conversely, improving efficiencies in water use and distribution could result in less energy consumption. As SADC countries are experiencing an expansion in industrial development and agricultural production, water and energy supply play a critical role if the SDGs and regional economic targets are to be achieved.

### *An Overview of the Southern African Development Community*

The Southern African Development Community (SADC) region is a southern African economic bloc of 15 member states—Angola, Botswana, Democratic Republic of Congo, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Swaziland, Tanzania, Zambia and Zimbabwe as shown in Figure 1. The region covers a land area of approximately 554,919 km$^2$ with a population of about 277 million people [14]. It was transformed in 1992, having been previously referred to as the Southern African Development Coordinating Conference (SADCC) which had been formed in 1980. The SADCC was mainly a political grouping aimed at countering the economic and political threat of apartheid South Africa [15]. As such, post-1990 with the expectation of a new political dispensation in South Africa, the region regrouped as the SADC.

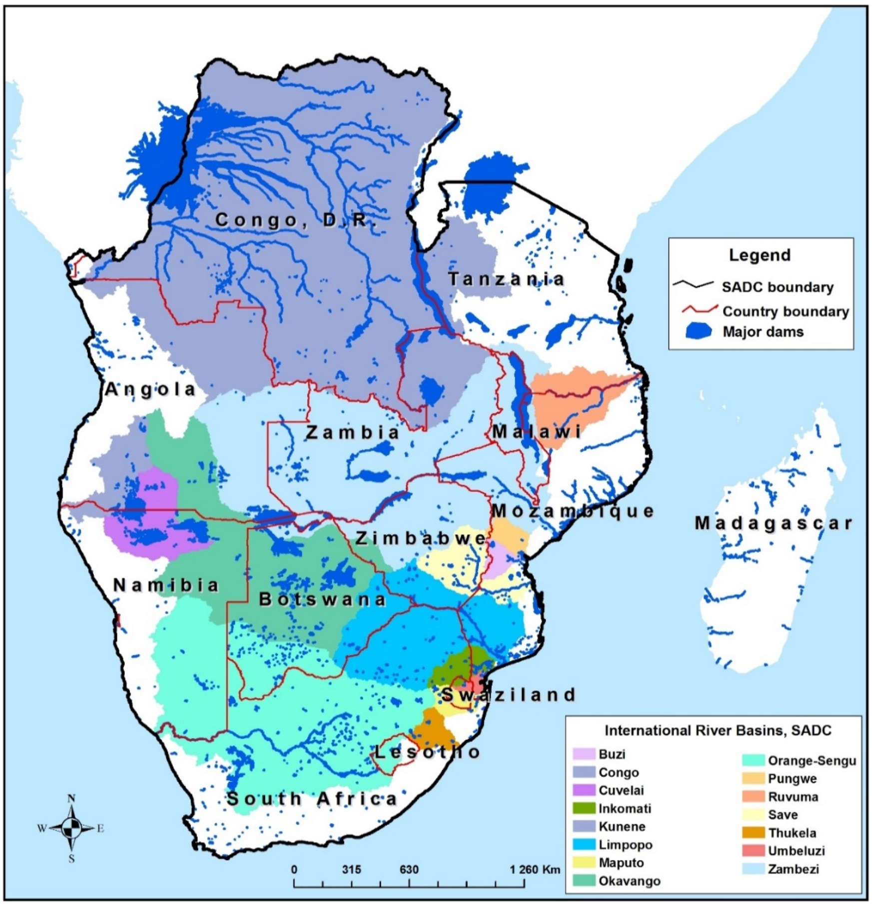

**Figure 1.** The countries that make up the Southern African Development Community's (SADC) 15 member states and the transboundary river basins within the bloc. Madagascar, Mauritius and Seychelles are the island states.

Countries within SADC share a common culture, heritage and socio-economic conditions. They also share similar bio-physical constraints with 85% of the region's water resources being transboundary e.g., the Zambezi River, as indicated in Figure 1. This often means that water resource management has to be transboundary as upstream water use affects water availability downstream. The countries also share the same energy grid, with several countries within the region exporting and importing power from each other to meet local demand. In this regard, this review pays particular attention to the 12 inland countries of the bloc as three—Madagascar, Mauritius and The Seychelles—are islands and therefore do not share water and energy resources with the others. The sharing of water resources and energy infrastructure within the region implies that the region has a greater need for a water–energy nexus approach. While issues of national sovereignty would dictate that member states pursue individual agendas for the attainment of water and energy security, this goal may be attainable when considered from a regional perspective.

## 2. Overview of the SADC Region's Water Resources

As previously alluded to, most of the SADC countries have similarities in terms of hydrological systems or conditions, and climate as well as water resource governance. Although 75% of the SADC region is classified as arid to semi-arid, its climate varies from desert, through temperate, savannah and equatorial [16]. Rainfall patterns in the region are largely governed by the position of three systems; the Inter-Tropical Convergence Zone (ITCZ) near the Equator, high-pressure cells south of the 20° S parallel, and cold fronts at the southern tip of the African continent. Average annual rainfall ranges between 100 and 2000 mm/year. The region has 15 transboundary river basins with a total mean annual runoff (MAR) of 650 $km^3$. Eighty-five percent of these river basins are shared. Figure 1 is a locational map of the SADC countries within Africa. The map also shows the transboundary river basins within the region. There is great variability in climate and water resources between different parts of the SADC region with great temporal variability [17], especially in the southern drier countries. For several decades, droughts have been broken by large scale floods, with very few years receiving the supposed average rainfall [17]. The variation in rainfall distribution changes from year to year and from country to country [18].

Projections of economic development and population growth in the region have led to predictions that several of the SADC states will become "water stressed" by 2025 [19]. The countries that would mostly be affected include South Africa, Namibia, Botswana and Zimbabwe. Other projections suggest that only South Africa will reach physical water scarcity with the rest of the region experiencing economic water scarcity as shown in Figure 2 [20]. Physical water scarcity implies that those countries will not be able to meet projected water demands in 2025, even after accounting for future adaptive capacity, while economic water scarcity refers to those countries that have sufficient water resources but lack the necessary infrastructure to make water available to users [20]. In addition to natural factors affecting the region's water resources, human activities interact and converge to create pressures on water resources, for which there are no substitutes [21]. These pressures are, in turn, compounded by factors such as varying levels of technological development, political, institutional and financial conditions, and climate change and variability across the region. As a result of these factors, it is estimated that most of the SADC countries will be importing 10% of their cereal requirements by 2025 if no measures are taken to reduce vulnerability.

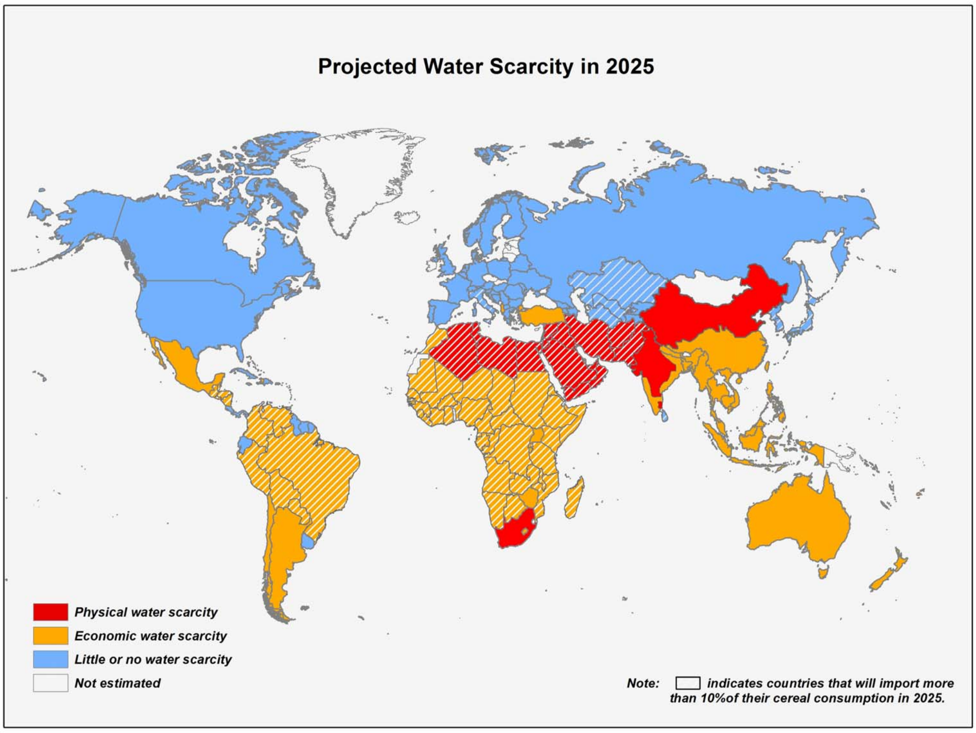

**Figure 2.** Projected physical and economic water scarcity by 2025 in the SADC region compared with the rest of the world. Source [20]. Note: countries marked with stripped yellow and red lines indicate those that although the respective countries show economic water scarcity, they will however have physical water scarcity by 2025 if no remedial solutions are taken now. The countries marked with stripped blue lines show countries that although they have little or no water scarcity, the trend is moving towards water scarcity by 2025.

Current predictions indicate that the global population will reach 9.3 billion by 2050 [22]; much of this growth is expected to occur in sub-Saharan Africa and Asia, mostly in urban areas. These projections imply that regional water demand for agriculture, domestic and energy generation will increase. This also places emphasis on the region's economic development as it strives to provide a better life for its growing population—water and energy are key to economic development and the attainment of a better life.

There is an urgent need to identify water resources that can be used to meet the increased demand for water from various sectors. Efforts are also being made at improving water use efficiency in various sectors, chiefly agriculture and energy generation. Already, economic development within the region is being frustrated by energy shortages. Spatial and temporal variability of water resources across countries within the region has led to large-scale development of water storage and transfer infrastructure [17,23]. In this regard, South Africa and Zimbabwe are ranked amongst the top 20 large dam builders in the world by the World Commission on Dams. However, not all of these dams are used for hydropower generation; most have been developed to meet irrigation and domestic water use. In such instances, the development of such dams can also add to demands on the energy grid as energy is required to pump water in irrigation and to treat and distribute water for domestic water use. Failure to consider these factors has sometimes led to dams not being utilised for those intended purposes; thus, they have failed to deliver the goals they were built to achieve.

There are two hydrologically important factors in the SADC region:

(a) the high number of transboundary rivers and the importance of these rivers to national populations. Five of the SADC states have water resources dependency ratios of over 50%—*i.e.*, they rely on water generated outside their borders to supply more than half of their total water resource stock [17,24]; and

(b) the reliance on groundwater—several of the SADC's member states share same aquifers. In the SADC region, currently very little is known about these aquifers [24]. The majority of them are not coincident with major river basins in the region—instead forming a stock of fossil groundwater. Currently, the flow characteristics, recharge rates, permeability and transmissivity of these water bodies is not well-understood [17,24].

This highlights the need for coherent water policy within the region. Individual member states like South Africa have made strides in understanding the hydrological factors that relate to their national water security. At a regional level, SADC member states are making strides in undertaking studies on transboundary water resources and formulating policies that govern transboundary river basins through the formation of Transboundary Watercourse Commissions such as the Zambezi Watercourse Commission (ZAMCOM) and Limpopo Watercourse Commission (LIMCOM), among others.

### *2.1. Water Scarcity within the Region—Is It Real or Fiction?*

The degree of aridity (water stress or scarcity) in the SADC countries was estimated using the Climatic Moisture Index (CMI). The CMI is an index of the relative dryness or wetness of an area, and it defines the water stress or scarcity (aridity) of a region. It is based on the combined effect of temperature and precipitation as it is linked to soil moisture, and therefore it is correlated with potential evapotranspiration. The CMI is calculated based on the methodology developed by Willmott and Feddema [25], using the ratio of annual precipitation (P) to annual potential evapotranspiration (PET), as indicated by Equations (1) and (2):

$$\mathrm{CMI} = \frac{\mathrm{P}}{\mathrm{PET}} - 1, \text{ when } \mathrm{P} < \mathrm{PET}, \text{ and} \tag{1}$$

$$\mathrm{CMI} = 1 - \frac{\mathrm{PET}}{\mathrm{P}}, \text{ when } \mathrm{P} \geqslant \mathrm{PET} \tag{2}$$

The index ranges from $-1$ to +1, with wet climate showing positive CMI and dry climate negative CMI. The CMI is an aggregate measure of potential water availability imposed solely by climate.

The PET of each country was calculated from data recorded from weather stations within the region and the results interpolated in GIS to create a continuous PET surface. The Thiessen's Polygon method was then used to calculate the area weighted average PET for each country. The CMI was calculated for four years *i.e.*, 1980, 1990, 2000 and 2007 and the results were then used to assess the aridity of the region.

Table 2 presents the CMI of SADC countries, which are all negative. The negative CMI values indicate that the PET in the region exceeds precipitation. According to Vörösmarty *et al.* [26], there is a classification link between CMI values and climatic conditions (CMI < −0.6 = Arid; −0.6 < CMI < 0 = Semi-arid; and CMI > 0 = Humid). The average CMI for the SADC region for the years under observation was calculated as −0.80, qualifying the region to be a dry and water-scarce region according to Vörösmarty's classification [26]. The aridness of individual countries is increasing over the years, which is not an encouraging sign for agriculture and energy production where water plays a crucial role as an input to the production system.

**Table 2.** Water scarcity levels (Climatic Moisture Index (CMI)) of SADC countries.

| Country | Climatic Moisture Index | | | |
|---|---|---|---|---|
| | 1980 | 1990 | 2000 | 2007 |
| Angola | −0.80 | −0.78 | −0.93 | −0.81 |
| Botswana | −0.87 | −0.90 | −0.85 | −0.93 |
| Congo DR | −0.64 | −0.57 | −0.87 | −0.78 |
| Lesotho | −0.84 | −0.83 | −0.83 | −0.88 |
| Madagascar | −0.54 | −0.56 | −0.74 | −0.60 |
| Malawi | −0.66 | −0.77 | −0.88 | −0.75 |
| Mauritius | −0.04 | −0.55 | −0.66 | −0.58 |
| Mozambique | −0.73 | −0.76 | −0.87 | −0.84 |
| Namibia | −0.93 | −0.96 | −0.90 | −0.96 |
| Seychelles | −0.32 | −0.23 | −0.63 | −0.45 |
| South Africa | −0.86 | −0.87 | −0.86 | −0.90 |
| Swaziland | −0.71 | −0.81 | −0.78 | −0.88 |
| Tanzania | −0.73 | −0.70 | −0.88 | −0.79 |
| Zambia | −0.73 | −0.75 | −0.87 | −0.87 |
| Zimbabwe | −0.79 | −0.81 | −0.85 | −0.92 |
| Average SADC | −0.75 | −0.74 | −0.87 | −0.83 |

Besides the aridness of the region, the demand for freshwater resources continues to increase due to urban and industrial growth and agriculture expansion [27]. Based on the portion of renewable freshwater resources available for human requirements and taking into account the existing water infrastructure, most of southern Africa faces either economic or physical water scarcity. Economic water scarcity is when countries have adequate renewable resources with less than 25% of water from rivers withdrawn for consumptive use by humans, due to poor water infrastructure to make existing water resources available for use e.g., the Democratic Republic of Congo and Zambia. Physical water scarcity is when more than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes e.g., South Africa [20].

Poverty levels in the SADC region prevent many people from accessing adequate water for basic human needs, especially for domestic and household purposes as well as water for production. The problem of water scarcity is worsened by threat multipliers such as climate change. This has led to projections that countries that are currently classified as being physically water scarce may become water-stressed by the year 2025 [19]. As such, any planning for energy generation should explicitly include water and vice versa.

Generally, the SADC region is characterised by extreme climate events such as floods and droughts, caused by climate change and variability [28]. Currently (2015/16), the region is experiencing one of the worst droughts since 1991/92. The 1991/92 drought was one of the worst droughts previously experienced within the region [28,29]. The current drought has affected water levels in the Zambezi Basin with power generation at Kariba dam dropping by about a third in 2015. As the dam provides power to Zambia and Zimbabwe, the reduction in water levels due to the drought has led to load shedding in the two countries. In addition, ongoing repairs at Kariba dam and expansion projects to increase power generation also demand energy. This highlights water–energy nexus constraints.

The spatial-temporal distribution of the region's water resources, both surface and groundwater, is uneven [28]. After the 1991/92 drought, the SADC region proposed the development and implementation of regional integration and water resources management strategies [28,29]. However, the realisation of this initiative has not yielded tangible progress. This is despite the fact that SADC's water resources are an important component in realising sustainable social development in the region [28] and therefore should warrant better coordination among member states. The region's scarce water resources are responsible for meeting the domestic and industrial water requirements for a large and increasing population as well as sustaining a rich diversity of natural ecosystems [19,30]. In addition, the same water resources are critical for increasing food security; irrigated agriculture accounts for between 60% and 90% of water withdrawals while water productivity in rainfed agriculture is low. Furthermore, the same water resources are utilised in energy generation which is also transboundary. The demand on the scarce water resources from non-energy sectors of the economy highlights a need for integrated water–energy nexus planning at a regional level.

Currently, there is a mismatch between available water resources and demand across the whole region. The mismatch implies that, with the region being water scarce, the demand for water from various end users is often higher than water supply. The water infrastructure (*i.e.*, agriculture, food security and rural livelihoods, energy, water supply and sanitation) [31] is unevenly developed across the region so that there is unequal allocation of water among sectors like agriculture, mining, forestry and industry [28]. The development of such infrastructure will in itself require significant energy outlays. In the absence of meaningful regional cooperation and integrated water resources management, water scarcity in some parts of the SADC region and competing developmental requirements between member states may result in future disputes and tension over water [28].

### 2.2. Water Requirements for Energy Generation

Water is required at various stages of the energy production chain as indicated in Figure 3. For instance, the extraction, processing and transportation of fuels require water. In addition, construction of power plants and generation also demands water. The required volume of water varies with the energy technology. At each stage, a volume of water (W) is withdrawn from a reservoir. Part of this water is consumed (C) while the remainder is discharged (D) back into the water source. In some cases, a proportion of the withdrawn water is recycled (R). Table 3 shows estimated water intensities on a lifecycle basis. It is observed from this table that solar photovoltaic (PV) and wind technologies demand minimal quantities of water, with most of the water being used in the upstream stages of power production (such as material extraction and processing, and manufacturing of plant components). Wet-cooled concentrated solar power (CSP) has a higher water intensity compared to PV and wind technologies.

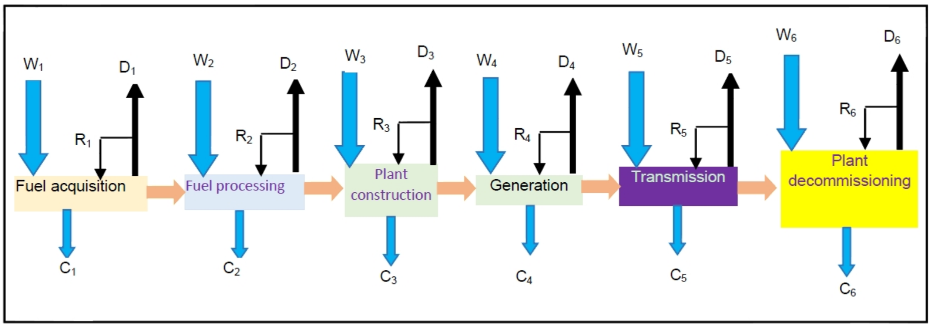

**Figure 3.** Water requirements in the water production chain.

**Table 3.** Water withdrawals on a lifecycle basis. Source [32].

| Technology | Water Intensity (Litre/MWh) |
|---|---|
| Coal | 1284–194,428 |
| Hydro | 80–440,000 |
| Nuclear | 4512–119,415 |
| Oil/gas/steam | 1489–86,971 |
| CSP (wet-cooled) | 500–5000 |
| Photovoltaic (PV) | 276–1957 |
| Wind | 170–324 |
| Geothermal | 12,800–344,700 |

The International Energy Agency (IEA) [33] recently forecast a more water constrained future due to climate change, population growth and global economic challenges. These multiple stresses will impact the energy sector with regards to the reliability of energy generation and supply as well as associated energy costs [33]. Southern Africa is expected to experience all these stresses. This, against the backdrop of already scarce water resources, suggests a more water constrained future with significant impacts on energy generation and costs. This will affect the development agenda within the region which, although not explicitly stated, relies to a large extent on availability of energy to support plans for industrialisation as enunciated in the SADC Industrialisation Strategy and Roadmap [34]. Already, growth forecasts for the region, especially regional powerhouse South Africa, have been reduced due, in part, to critical energy shortfalls. This again demonstrates that the water–energy nexus approach is pivotal to regional economic development.

The IEA [33] stated that the water requirements for fossil fuel based and nuclear power plants—the largest users of water in the energy sector—could be reduced significantly with advanced cooling systems. However, most of the region's coal power plants are old and use old technology [35–37], hence they use significant amounts of water. The expansion of coal power generation within the region will also have effects on regional water resources as this will increase water requirements for energy generation.

Recently, there have been proposals among southern African states for biofuels feedstock production for energy generation. Individual member states (e.g., South Africa and Zimbabwe) are making different levels of progress with regards to the use of biofuels and establishing a policy framework for their adoption. There are reports from elsewhere indicating that, if irrigated, the water footprint of biofuels could be unacceptably high [21]. The IEA [33] outlined that future water needs for biofuels depend largely on whether feedstock crops come from irrigated or rainfed lands and the extent to which advanced biofuels whose feedstock crops tend to be less water-intensive are utilised. In South Africa, a draft Biofuels Regulatory Framework [38] explicitly states that irrigation will not be considered for biofuels feedstock production. However, the draft makes it possible for exceptions to be made in cases where groundwater would be used for such irrigation. This proposal does not consider the significant energy requirements for pumping and distributing groundwater for irrigation.

## 3. Overview of the SADC Region's Energy Resources and Infrastructure

Economic growth is perceived to be unsustainable if it demands a lot of energy, generates significant pollutants, and negatively affects public health [39]. Moreover, fossil energy resources occur in finite quantities, and so will eventually run out. In view of this, SADC countries are making policy shifts to increase the uptake of renewable energy technologies. In this regard, SADC recently published a status report on renewable energy [34] in which it recognised the need to create new opportunities for renewable energy across the region.

Southern Africa is endowed with traditional and modern energy sources, with the energy mix varying from one country to another. In general, woody biomass is the major source of energy in most of the countries in the region [40]. Apparently, the heavy dependence on this resource is contributing to deforestation, climate change and other associated environmental problems, which threaten water security. Loss of forest cover reduces infiltration of rain water into the soil and it enhances soil erosion and siltation of reservoirs of surface water, thereby diminishing the quantity of water resources. Moreover, soil erosion contributes to the deterioration of the quality of water aquifers. Some parts of the SADC region may experience reduced levels of rainfall due to climate change. The distribution of forest products for some SADC countries is presented in Table 4. DR Congo exhibits the highest levels of production of round wood and wood fuel.

**Table 4.** Forest products for some SADC countries. Source [41].

| Country | Industrial Round Wood (1000 m$^3$) | Round Wood (1000 m$^3$) | Wood Fuel (1000 m$^3$) | Wood Charcoal (1000 tons) |
|---|---|---|---|---|
| Botswana | 105 | 760 | 655 | 65 |
| DR Congo | 3653 | 73,430 | 69,777 | 1646 |
| Malawi | 520 | 5622 | 5102 | 426 |
| Mozambique | 1319 | 18,043 | 16,724 | 1000 |
| South Africa | 21,159 | 33,159 | 12,000 | 201 |
| Swaziland | 330 | 890 | 560 | - |
| Tanzania | 2314 | 23,819 | 21,505 | 1328 |
| Zambia | 834 | 8053 | 7219 | 1041 |
| Zimbabwe | 992 | 9108 | 8115 | 9 |

Biomass can be converted to different forms of energy using various processes. The key processes are:

(a) First generation: uses agricultural crops (such as grain, sugar cane, soy bean) as a feed stock to produce biogas, bioethanol or biodiesel. First generation technologies are mature enough but feedstock crops are traditionally produced for food consumption. Bioethanol is the largest biofuel and it is mostly produced from corn and sugar cane [42]. So, the first generation biofuels interfere with food security. In addition, the production of crops for first generation biofuels competes for water.

(b) Second generation: uses non-food feedstock, especially lignocellulosic biomass, to produce a biofuel [43]. The feedstock can be sourced from crop, forest and wood-process residues, thereby reducing the interference with food security. Another advantage is that the use of residues promotes efficient use of water. Nevertheless, producing biofuels from lignocellulose is not cost-effective [44] due to technical barriers.

(c) Third generation: biofuel is produced from algae or cyanobacteria that contain a high proportion of oil mass [44]. Algae can be cultivated by using water of low quality, not suitable for human consumption. Oil from these organisms can be used as a raw material for producing biodiesel while the carbohydrate components can be converted into bioethanol.

Jumbe *et al.* [45] assessed all the biofuel products available on the market. They concluded that ethanol is the most promising biofuel which can be produced from different raw materials in Africa. Within the SADC region, Malawi is producing (from sugar molasses) about 30 million litres of ethanol per year which is blended with imported petrol [36,45]. Zimbabwe started a similar initiative but the country exports all the produced ethanol. There are also biofuel initiatives in other countries such as Mozambique, South Africa and Zambia.

The region is also endowed with oil and natural gas resources. Angola has the highest oil reserves but most of the crude oil is exported outside the SADC region [36,40]. Consequently, SADC countries predominantly import oil from other regions. Crude oil is also produced in the Democratic Republic of Congo (DRC) and South Africa. In 2014, petroleum and other liquid production in Angola was 1,756,000 barrels (bbl) per day [46], with the country placed at position number 16 on the world ranking of producers of this category of products. At present, most of the oil refining within the region is done in South Africa [36]. Oil refineries in Tanzania and Zimbabwe were mothballed due to liquidity crisis. A summary of the crude and refined oil production in the region is presented in Table 5.

**Table 5.** Crude and refined oil production in SADC. Source [36].

| Country | Crude Oil (bbl/day) | Refinery Capacity (bbl/day) |
|---|---|---|
| Angola | 1,250,000 | 39,000 |
| DR Congo | 20 | - |
| Madagascar | - | 15,000 |
| South Africa | 215 | 504,547 |
| Tanzania | - | 14,900 |
| Zambia | - | 23,750 |

Transportation of oil products across the region is bottle-necked by availability of appropriate infrastructure. In view of this, refined petroleum products are shipped by road and rail to market points. A limited number of pipelines are in operation across the region. For instance, the Tazama pipeline conveys crude oil from Dar-es-Salaam in Tanzania to the Indeni Refinery in Zambia.

It is known that the SADC region has about 9.135 trillion cubic feet (Tcf) of proven reserves of natural gas in Mozambique, Namibia, Angola, Tanzania and the DRC as shown in Figure 4. Opportunities exist for the region to meet its energy demand from natural gas and hydro resources [47] but this has implications for the water requirements for energy production [48]. It is worth noting that Mozambique holds most of the natural gas reserves in this region. For infrastructure, there is a Mozambique-South Africa gas pipeline along the Maputo Corridor.

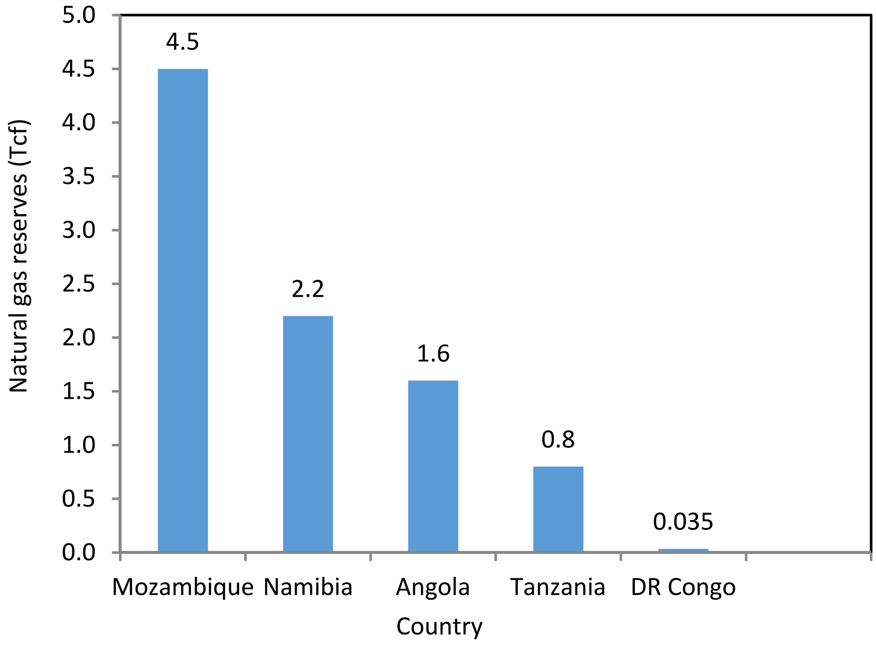

**Figure 4.** Reserves of natural gas in SADC. Source of data [41].

Large proven reserves of coal are found in Botswana, Mozambique, South Africa, Zimbabwe and Swaziland, with South Africa accounting for about 90% of Africa's proven reserves of coal [40]. The produced coal is mainly used for generating electricity, in addition to exportation. For example, Dekker *et al.* [49] reported that 68% of electricity in South Africa was produced from coal-fired plants. Currently, the country is expanding its coal power generation capacity, including two coal-fired power plants (Medupi and Kusile plants) near completion. This has led to new coal mining concessions being granted with an increase in water required during the pre-generation stage of electricity. Zimbabwe is also expanding its coal generating capacity in similar fashion, although at a smaller capacity. Most (75%) of the power in SADC is generated from coal, which generally dominates the southern part of the region [48].

The SADC region has enormous potential for hydropower, especially in Angola, DRC, Mozambique and Zambia. Hydropower is most prevalent in the northern part of the region, and the total regional hydropower potential has been assessed to be about 1080 terawatt hours per year (TWh/year) but the current level of exploitation of this resource is less than 31 TWh/year [47]. The solar and wind resources are also significant in the region but only a small proportion is exploited to provide the needed amount of energy. There has been limited expansion of power generation from renewable sources within the region due to technical, financial, policy, regulatory and political challenges [50]. Nevertheless, it should be pointed out that SA has made significant progress in promoting the exploitation of renewable energy resources at the national level. The Department of Energy in the country developed an Integrated Resource Plan (IRP) to meet future electricity demand and other government objectives, and to reduce greenhouse gas emissions [51]. In line with this, a Renewable Energy Feed-in Tariff (REFIT) was introduced in 2009 and later, in 2011, revised to the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) with a bidding process. The power generated by the independent power producers is fed to the national grid through a power purchase agreement. So far, this programme has proved to be successful in many respects including the diversification of power producers from a single to 64 power producers in the first three rounds of bidding, and reduction in the price of electricity [52]. There is an opportunity to replicate some of the successful factors in other developing countries, including those in the SADC region. Access to electricity is low in most of the member states, with South Africa having the highest rate of access.

To strengthen regional cooperation in the energy sector, the Southern African Power Pool (SAPP) was established in April 1995 to optimize the exploitation of available energy resources [53]. This regional grouping was aimed at promoting economic cooperation among the member countries. Schreiner and Baleta [47] have observed the following challenges encountered by SAPP:

(a) there is lack of investment in energy infrastructure by member states, and
(b) the federalization of energy generation is predominantly dependent on South Africa as the largest energy consumer in the region. Nevertheless, this country has been concentrating on internal energy generation to meet domestic demand.

As regards the possible cooperation on the energy–water nexus, it would also require investment in energy and water infrastructure by member states. Thus, lack of financial support may still prevent such cooperation. At present, South Africa is already examining the energy–water nexus at the national level through various instruments and initiatives. The IRP identifies water as a key constraint and risk, and this factor is included in the long-term energy scenarios over the time horizons of 2030 and 2050. South Africa has also developed an energy efficiency policy which is beneficial to the water sector (reduction in energy consumption saves water required for energy production. The national electricity utility of South Africa (Eskom) has embarked on a number of initiatives to enhance efficient use of water, including desalination and the development of dry-cooled power plants. The foregoing discussion shows that national issues take precedence over regional demands. This challenge may be exhibited in a regional cooperation on the energy–water nexus.

### 3.1. Energy Crises

Although biomass is the main source of energy in the region, the onset of droughts, land clearance for agriculture and other anthropogenic activities are contributing to its loss. As a result of this, some parts of the region are under threat from desertification. Figure 5 depicts that the levels of the fraction of wood fuel production in total round wood are lowest and highest in South Africa and DR Congo, respectively. This observation is attributed to the higher proportion of round wood consumption for industrial application (0.64) in South Africa compared to that in DR Congo (0.05). The average value of the fuel wood fraction is 0.81, which compares very well with findings (0.9) by Dasappa [42] for the African continent.

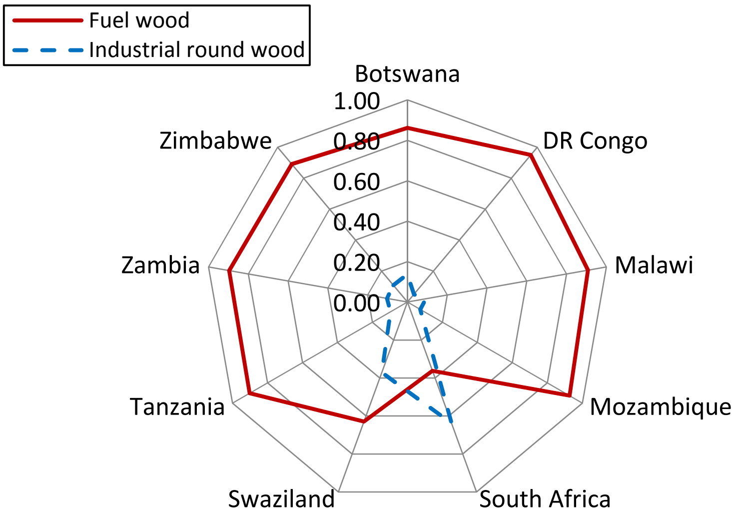

**Figure 5.** Fractions of wood fuel production and industrial round wood in round wood production in SADC. Source of data [42].

Population and industrial growth are increasing the demand for energy thereby, aggravating the energy shortage in the region (Figure 6). Using 2014 as a base year, the demand for power will increase by 44% in 2025. Capacities for electricity generation can hardly meet the local electricity demands in some of the member states as shown in Table 6. Consequently, there is a total generation capacity shortfall of 8247 MW, taking into consideration the reserve margins [54]. It should be noted that South Africa has the largest installed capacity in the region, with most of the electricity being generated by coal-fired power plants [49,55]. However, the heavy reliance on this type of fuel is contributing to high carbon emissions. Some of the utilities are implementing load shedding policies to meet the local electricity demand. The average number of days/month of outage of electricity in 2008–2009 in sub-Saharan Africa was 10.3 with each outage lasting an average of 6.70 h [56].

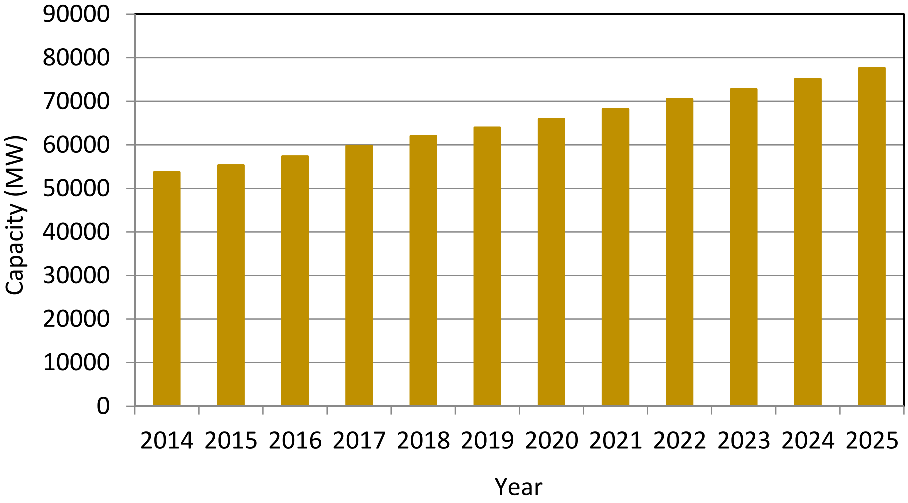

**Figure 6.** Southern African Power Pool total forecast demand. Source of data [55].

**Table 6.** SAPP utility general information [57].

| Country | Installed Capacity (MW) | Net Capacity (MW) | Maximum Demand (MW) |
|---|---|---|---|
| Angola | 2210 | 1805 | 1599 |
| Botswana | 892 | 460 | 610 |
| DR Congo | 2442 | 1485 | 1381 |
| Lesotho | 72 | 72 | 150 |
| Malawi | 351 | 351 | 326 |
| Mozambique | 2308 | 2279 | 830 |
| Namibia | 501 | 392 | 629 |
| South Africa | 46,963 | 41,074 | 36,170 |
| Swaziland | 70.6 | 70 | 221 |
| Tanzania | 1380 | 1143 | 935 |
| Zambia | 2128 | 2029 | 1987 |
| Zimbabwe | 2045 | 1600 | 1671 |
| Total | 61,362.6 | 52,760 | 46,509 |

It has been widely acknowledged that the SADC region is faced with significant energy challenges [34]. These are intricately related to the regional goals such as rural electrification, delivering on social and economic development targets and developing the existing electricity infrastructure to meet the rising demand [34]. The goal of increasing energy generation is hindered by the old and outdated energy generation infrastructure which is very expensive to maintain and/or replace. Such is the extent of the crises that the region now recognises the need to make critical decisions across its energy sectors to ensure that there is increased access to energy in all sectors [34]. While this need to increase energy generation in order to avert the crises has been recognised, the linkages between water and energy have not yet been recognised as yet. There is disconnection between regional energy and water planning with the two resources often being discussed at separate forums and regional policy lacking convergence. The regional drive to increase electricity generation will surely lead to increases in water use for energy generation; this highlights the need for a water–energy nexus approach given that the region also faces increasing water scarcity.

### 3.2. Energy Requirements for Water

Energy is required in all stages of the water production chain. In this regard, the major processes in the water production chain are construction, operation and maintenance of water supply facilities; abstraction and conveyance; treatment (desalination and other); and collection and treatment of wastewater as demonstrated in Figure 7 A given process converts part of the input energy into useful energy (U) while the rest is dissipated from the process. In some cases, a proportion of the dissipated energy is recovered (V), with the remainder being rejected as waste energy. Abstraction and conveyance involves pumping (withdrawal) of water from surface and ground sources and transporting it to treatment and storage facilities. The total energy (E) consumed in the water production chain can be given by:

$$E = \sum_{i=n}^{i=n} E_i \tag{3}$$

where n = number of stages.

Groundwater and desalination were the most common sources of water in the Middle East and North Africa region [2]. Apparently, both desalination and groundwater pumping are energy intensive. Based on the data reported by Siddiqi and Anadon [2], the estimated values of energy intensities for groundwater withdrawal in Libya (at a depth of 400–1200 m) and Saudi Arabia (at a depth of 100–180 m) were 1.558 kWh/m$^3$ and 0.389 kWh/m$^3$. The difference in energy intensity for abstracting water from the ground between the two countries is ascribed to the depth at which the groundwater aquifer is located.

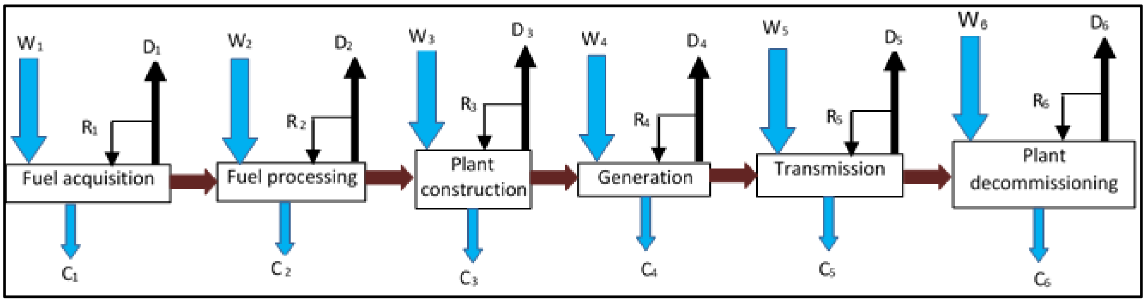

**Figure 7.** Energy requirement in the water production chain. $E_i$ is the energy input with corresponding useful ($U_i$), recovered ($V_i$) and waste ($S_i$) energy at the ith stage of water production chain, where i = 1,2,3, . . . , n, and n is the number of stages.

Depending on the quality of the raw water and intended end-use, treatment (such as desalination) may be required before it can be used. There are two broad classes of conventional techniques for desalination [58]: thermal and membrane based. The former category includes multi-stage flash distillation (MSF), multi-effect distillation (MED) and vapour compression distillation (VCD); while the latter class comprises reverse osmosis (RO), nanofiltration (NF) and electrodialysis (ED). In thermal desalination, salts are removed from water by evaporation-condensation processes. Membrane based techniques employ a membrane through which water diffuses with a high proportion of the salts being retained. However, these techniques require a large input of energy. The energy intensity of various desalination processes is presented in Table 7. It is observed that the MED process exhibits the lowest demand for energy per unit volume of fresh water produced. Nevertheless, the intensity of energy for pumping groundwater from shallower levels would be lower compared to the desalination process. Moreover, the quality of some raw groundwater may meet acceptable standards without needing purification, thereby diminishing the energy demand.

**Table 7.** Energy intensity of various desalination processes. Source [2].

| Process | Electrical Energy Use (kWh/m$^3$) |
|---|---|
| RO | 2.6–7.0 |
| MFS | 3.0–5.0 |
| MED | 1.5–2.5 |

Similarly, the distribution of water requires energy for batch or continuous processes. In rural or isolated areas, water may be distributed by using vehicles (such as tankers) or labour-intensive (for instance, the use of buckets to fetch water) methods. The use of motorised technologies to distribute water requires energy, and diesel is commonly used to drive such technologies in developing countries. On the other hand, labour-intensive and gravity-fed water supply systems have low energy intensity and are exploited in some parts of the SADC region.

Water is used (with associated energy demands) in different sectors of the economy. For example, various industrial and domestic processes use energy to produce steam or hot water. The water heating processes have high energy intensities, especially the vaporization process. The specific heat capacity and latent heat of vaporisation of water are about 4.18 kJ/(kg· °C) and 2256 kJ/kg. This indicates that hot water and steam production are energy intensive. The water production chain also includes the wastewater treatment stage which is also driven by energy. For the Middle East and North Africa region, Siddiqi and Anadon [2] assumed energy intensity values of 0.1–0.3 kWh/m$^3$ and 0.272–0.59 kWh/m$^3$ for primary and secondary wastewater treatment (activated sludge), respectively.

In some of the SADC countries including South Africa, more than 21 million cubic metres of water is withdrawn daily from surface and ground water resources of freshwater and saline—water to supply domestic uses, agriculture including irrigation, mining, industry and thermoelectric power. However, information about the energy requirements for water pumping, purification and conveyance, and wastewater treatment is fragmentary and not well documented overall. Gulati *et al.* [59] reported that the energy need for water in South Africa will increase with (i) demand for water due to population and economic growth; (ii) need to pump deeper ground water; and (iii) the exploitation of alternative water resources (such as sea water). However, data is scarce on the intensity of energy for water production in South Africa, with a similar trend being observed in the other member states of the SADC region.

## 4. Southern Africa's Water–Energy Nexus

As already highlighted, water plays a critical role in energy generation while energy is used the water production chain [2]. The interrelatedness between water and energy has given rise to the water–energy nexus. Issues related to water and energy have been discussed at different fora and constraints and vulnerabilities associated with the water–energy nexus have been outlined on several occasions. It is well documented that energy generation requires water, often in large quantities or volumes, for fuel production, mining, hydropower and power plant cooling [33]. Statistics for actual water demands by region or country vary and are poorly documented. International averages on water factors are presented in Table 8 as well as data on installed generation capacity reported by SAPP [54]. Plant capacity factors used in this study are also included in Table 8.

**Table 8.** Installed generation capacity [54], assumed capacity factors and annual water withdrawal for the various energy technologies exploited within SAPP.

| Technology | Installed Generation Capacity (MW) | Capacity Factor (%) | Annual Water withdrawal ($\times 10^9$ Litres) |
|---|---|---|---|
| Hydro | 13,000 | 90 | 22,552 |
| Coal | 38,381 | 85 | 27,966 |
| Nuclear | 1860 | 90 | 909 |
| OCGT * | 936 | 20 | 73 |
| Distillate ** | 2709 | 20 | 210 |
| Wind | 2492 | 30 | 2 |
| Solar CSP | 600 | 20 | 3 |
| Solar PV | 1821 | 25 | 4 |
| Landfill | 18 | 30 | 2 |
| Biomass | 42 | 60 | 10 |
| Total | 61,859 | | 51,730 |

Notes: * OCGT: Open cycle gas turbine; **: Petroleum fuel produced through conventional distillation.

For conventional fuels, coal-fired thermal power plants withdraw the highest amount of water from reservoirs. This elevated magnitude of water is attributed to the high proportion of installed capacity, capacity factor and water intensity of coal. South Africa is implementing drying cooling in some of the coal-fired plants reduce the water footprint. The Open Cycle Gas Turbine (OCGT) and distillate technologies have relatively lower water intensity compared to coal and nuclear technologies. The existing Koeberg nuclear power plant in South Africa, with an installed capacity of 1800 MW, uses seawater for cooling, and therefore does not compete for the limited fresh water in the country. For renewable energy technologies, hydro energy power exhibits the largest amount of water demand, with PV and wind being the most water-efficient over the considered stage of the lifecycle. It should be mentioned that hydro power has a wide range of water intensity reported in literature. However, it should be noted that water provides the driving force for hydro power plants, which implies that scarcity of this resource poses a high risk to the production of hydro power.

In 2013, about 77% of the installed capacity of electricity generation in the SADC region was in South Africa. In addition, a large proportion of electricity is generated by coal-fired thermal plants in South Africa [49], which are predominantly wet-cooled. However, wet-cooled coal-fired power plants withdraw high amounts of water from reservoirs on a lifecycle basis [32]; water consumption and withdrawals range between 1000 and 10,000 $m^3$, respectively [60]. Thus, most (75%) of the electricity produced in the region [47] is not sustainable from a water perspective. Energy is also needed for pumping, treatment and distribution of water as well as for collection, treatment and discharge of waste-water. About 300 of the 800 million people in sub-Saharan Africa have less than 1000 $m^3$ of water per capita [61]. The SADC mirrors this; many people still lack access to water for basic needs and sanitation, and access to safe water is a constitutional right in several SADC states. Similarly, most people still lack access to electricity and rely on biomass for energy generation; figures indicate that only 5% of SADC's rural areas have access to electricity. In South Africa, the regional economic powerhouse, 15.3% and 8.5% of the population still lack access to electricity and safe water, respectively. The values are even higher in Malawi, where 93% and 16.3% of the population lack access to electricity and water, respectively [21]. At the same time, the region faces increasing water scarcity and declining energy generation capacity as it tries to move forward and develop. This interrelationship is what is often referred to as the water–energy nexus.

The water scarcity of the region is placing an economical or physical constraint to water resources. The situation is worsened by increasing population, agricultural expansion and industrialisation. Currently, most of the region's water resources (>70%) are used in agriculture, with the remainder being used for domestic, industrial and power generation purposes. The major goal of the region is to ensure delivery of clean water and energy to its growing populace, especially in rural areas. Programmes such as rural electrification aimed at correcting historical social injustices also add to power demand. Consequently, several countries within the region now experience frequent load shedding as power utilities within the region seek to regulate power distribution during peak periods. Thus, the region faces water and energy challenges which are constraining the water–energy nexus.

As the region moves to adopt the SDGs, their attainment will depend, to a large extent, on how the region's water–energy nexus is managed. Economic development as envisaged in the SADC Regional Indicative Strategic Development Plan [37], based on industrialisation, will require availability of electricity to power current and new industries. Furthermore, foreign direct investment will also be stimulated if the region, as a whole, can provide evidence of water and energy security to encourage investor confidence. While the water–energy nexus presents many challenges to the region's development agenda, it also presents many opportunities for water and energy planning for development. These opportunities lie in integrated water resources management and use of renewable energy resources of which the region is well endowed with.

While the SADC region has long recognised that regional integration is central to addressing existing energy challenges and creating new opportunities for energy generation [34], it has not managed to link energy and water sector planning. Clearly, there can be no achieving one without the other, especially given the transboundary nature of water resources. The focus or bias on energy sector planning may be because while member states face varying forms of water scarcity (economic *vs.* physical water scarcity), they all share common challenges in terms of energy generation. This thinking is reflected in regional policy documents such as the SADC Protocol on Energy, the Energy Sector Plan of the SADC Regional Infrastructure Development Master Plan and the Regional Energy Access Strategy and Action Plan and the Regional Indicative Strategic Development Plan.

There is therefore a need for a paradigm shift in terms of how the region perceives its development agenda. Focusing on energy generation primarily without coordination with water sectors will not achieve meaningful regional integration nor will it fully deliver in improving the quality of life across the SADC. A coordinated water–energy nexus platform would have better prospects of delivering on social and economic goals.

## 5. Conclusions and Policy Implications

There is increasing demand for water and energy in the SADC region due to agriculture, population and economic growth. The region is characterised by economic and physical water scarcity. Currently, there is an energy crisis that is threatening economic development, raising the need for new energy generation projects. Concurrently, there is also an urgent need to identify water resources that can be used to meet increased demand for water from various sectors, including energy generation, across the region. These challenges will be exacerbated by climate change; there is a need to develop climate resilient water and energy sectors across the region, as well as promote climate smart agriculture. Adopting the water–energy nexus would not be a solution unless it is accompanied by an implementation plan. The lack of water–energy nexus planning across the SADC poses a serious threat to regional integration and development as well as to various sectors in terms of water allocation and energy supply. There is therefore an urgent need for the water–energy nexus to be adopted as an urgent sustainable solution to encourage SADC member states to plan their strategies, policies and interventions beyond their national borders. Regional water–energy nexus planning would be feasible since the region shares transboundary water and energy resources. This would then filter down to individual national planning, placing emphasis on inter-sectoral linkages and transboundary implications. If the water–energy nexus is embraced by all SADC states, issues related to regional integration would be driven in a sustainable and efficient way with strong coordination and support at technical and political levels. The following recommendations would be relevant to future work on developing policy on the water–energy nexus:

(a) Enhancing institutional arrangements for watercourses

- The water–energy nexus constraints vary within the region due to differences in water availability and energy technologies infrastructure. Temporal variability affects energy and water interactions. Reducing inefficiencies between the two sectors requires more effective dialogue and improved coordination for joint planning and execution of interdependent projects. In this regard, existing watercourse commissions (ZAMCOM, LIMCOM, ORESCOM, *etc.*) and the Southern African Power Pool (SAPP) need to be strengthened to foster integration and help the region in achieving the SDGs through the nexus thinking.
- Considering the transboundary nature of the watercourses in the SADC region, there is need to further explore ways of institutionalising the nexus approach in policy instruments beyond the watercourse commission approach. Opportunities exist in the region for virtual water transfers to be an important component of peaceful cooperation and shared growth in the sovereign interests of individual SADC states and shared economic growth could lie in pursuing regional water, food and energy security.

(b) Developing modelling capacity

- In order to champion the water–energy nexus, there is a need to improve modelling and also develop system-wide data for climate, weather and energy use in order to broaden understanding of water/energy interdependencies. More data is needed in order to develop data systems and models; this can improve our understanding of water–energy nexus initiatives now and in the future. This will lead to better informed decision making across the water–energy nexus.

(c) Improving collection, documenting, visualising and sharing of data

- There is a scarcity of data on energy consumption in the water sector within the SADC region. Statistics for actual water demands by region or country vary and are poorly documented. As such, further studies (at country and regional levels) are required to close this gap. While such data needs to be collected at the national level, it should be coordinated at the regional level. This will ensure that data can be shared at the regional level and used for input in data systems and models. The SADC region should strengthen links with data intense efforts such as Sustainable Development Goals and groups like the Group on Earth Observations (GEO) to help meet regional data and data infrastructure requirements.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Malik, R.P.S. Water–energy nexus in resource-poor economies: The Indian experience. *Int. J. Water Resour. Dev.* **2002**, *18*, 47–58. [CrossRef]
2. Siddiqi, A.; Anadon, L.D. The water–energy nexus in Middle East and North Africa. *Energy Policy* **2011**, *39*, 4529–4540. [CrossRef]
3. Olsson, L.; Yengoh, G.T.; Brogaard, S. Crop Water Requirements in Cameroon's Savanna Zones Under Climate Change Scenarios and Adaptation Needs. In *Crop Production Technologies*; InTech: Rijeka, Croatia, 2012.
4. Torcellini, P.A.; Long, N.; Judkoff, R. *Consumptive Water Use for US Power Production*; NREL/TP-550-33905; National Renewable Energy Laboratory: Golden, CO, USA, 2003.
5. Spang, E.S.; Moomaw, W.R.; Gallagher, K.S.; Kirshen, P.H.; Marks, D.H. The water consumption of energy production: An international comparison. *Environ. Res. Lett.* **2014**, *9*, 105002. [CrossRef]
6. Rasul, G. Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environ. Sci. Policy* **2014**, *39*, 35–48. [CrossRef]
7. Schnoor, J.L. Water–energy nexus. *Environ. Sci. Technol.* **2011**, *45*, 5065. [CrossRef] [PubMed]
8. Hussey, K.; Pittock, J. The Energy-Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. *Ecol. Soc.* **2012**, *17*, 31. [CrossRef]
9. Glassman, D.; Wucker, M.; Isaacman, T.; Champilou, C. *The Water–Energy Nexus: Adding Water to the Energy Agenda*; World Policy Institute: New York, NY, USA, 2011; p. 33.
10. Muller, M. The "nexus" as a step back towards a more coherent water resource management paradigm. *Water Altern.* **2015**, *8*, 675–694.
11. Rasul, G. Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environ. Dev.* **2015**. [CrossRef]
12. Wolf, A. Conflict and cooperation along international waterways. *Water Policy* **1998**, *1*, 251–265. [CrossRef]
13. Carius, A.; Dabelko, G.; Wolf, A. Water, conflict, and cooperation. *Environ. Chang. Secur. Proj. Rep.* **2004**, *10*, 60–66.
14. Kusangaya, S.; Warburton, M.L.; Van Garderen, E.A.; Jewitt, G.P.W. Impacts of climate change on water resources in southern Africa: A review. *Phys. Chem. Earth A/B/C* **2014**, *67*, 47–54. [CrossRef]
15. Southern Africa Development Community (SADC). *SADC Facts and Figures*; SADC: Gaborone, Botswana, 2012.
16. Masemola, H. *An Analysis and Appraisal of Restructuring in SADCC/SADC since 1990*; SADC: Gaborone, Botswana, 2009.
17. Malzbender, D.; Earle, A. Water resources of the SADC: Demands, dependencies and governance responses. In *Institute for Global Dialogue's (IGD) and Open Society Initiative for Southern Africa's (OSISA) Workshop on "Natural Resource Dependence in Southern Africa: Towards Equitable, Accountable and Sustainable Use"*; Institute for Global Dialogues and Open Society Initiative for Southern Africa: Pretoria, South Africa, 2007.
18. Hirji, R.; Maro, P. *Forthcoming—Defining and Mainstreaming Environmental Sustainability in Water Resources Management in Southern Africa*; SARDC: Harare, Zimbabwe, undated.
19. Southern Africa Development Community (SADC). *Regional Water Policy*; SADC: Gaborone, Botswana, 2006.
20. Seckler, D.W.; Amarasinghe, U.; Molden, D.; de Silva, R.; Barker, R. *World Water Demand and Supply, 1990–2025: Scenarios and Issue*; International Water Management Institute (IWMI): Colombo, Sri Lanka, 1998; Volume 19.
21. United Nations World Water Assessment Programme (WWAP). *The United Nations World Water Development Report 2014: Water and Energy*; UNESCO: Paris, France, 2014.
22. United Nations Department of Economic and Social Affairs (UNDESA). *World Population Prospects: The 2012 Revision, Highlights and Advance Tables*; Working Paper No. ESA/P/WP. 228; United Nations: New York, NY, USA, 2013.
23. Ashton, P.J. Avoiding conflicts over Africa's water resources. *AMBIO J. Hum. Environ.* **2002**, *31*, 236–242. [CrossRef]
24. Food and Agriculture Organization (FAO). *Aquastat Land & Water Use Data Base*; FAO: Rome, Italy, 2006.
25. Willmott, C.J.; Feddema, J.J. A more rational climatic moisture index. *Prof. Geogr.* **1992**, *44*, 84–88. [CrossRef]

26. Vörösmarty, C.J.; Douglas, E.M.; Green, P.A.; Revenga, C. Geospatial indicators of emerging water stress: An application to Africa. *AMBIO J. Hum. Environ.* **2005**, *34*, 230–236. [CrossRef]
27. Luo, Z.; Wang, E.; Fillery, I.R.P.; Macdonald, L.M.; Huth, N.; Baldock, J. Modelling soil carbon and nitrogen dynamics using measurable and conceptual soil organic matter pools in APSIM. *Agric. Ecosyst. Environ.* **2014**, *186*, 94–104. [CrossRef]
28. Msangi, J.P. Managing water scarcity in Southern Africa: Policy and strategies. In *Combating Water Scarcity in Southern Africa*; Springer: Berlin, Germany, 2014; pp. 21–41.
29. Mpandeli, N.S.; Maponya, P.I. Coping with Climate Variability in Limpopo Province, South Africa. *Peak J. Agric. Sci.* **2013**, *1*, 54–64.
30. Southern Africa Development Community (SADC). *Regional Water Policy*; SADC: Gaborone, Botswana, 2005.
31. Beetlestone, P. *Challenges to Transboundary Aquifer Management in the SADC Region*; SADC Infrastructure and Services Directorate—Water Division: Gaborone, Botswana, 2009.
32. Southern Africa Development Community (SADC). *Regional Water Infrastructure Programme*; SADC: Gaborone, Botswana, 2010.
33. Fthenakis, V.; Kim, H.C. Life-cycle uses of water in US electricity generation. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2039–2048. [CrossRef]
34. International Energy Agency (IEA). *Water for Energy, Is Energy Becoming a Thirstier Resource? Except from the World Energy*; IEA: Paris, France, 2012.
35. Stiles, G.; Murove, C. *SADC Renewable Energy and Energy Efficiency Status Report*; SADC: Gaborone, Botswana, 2015.
36. Zhou, P.P. *Regional Infrastructure Development Master Plan: Energy Sector Plan*; Southern African Development Community (SADC): Gaborone, Botswana, 2012.
37. Regional Indicative Strategic Development Plan (RISDP). *Regional Indicative Strategic Development Plan*; RISDP: Gaborone, Botswana, 2015.
38. Department of Energy (DoE). *Draft Position Paper on the South African Biofuels Regulatory Framework*; Department of Energy: Pretoria, South Africa, 2014.
39. Ben Abdallah, K.; Belloumi, M.; De Wolf, D. Indicators for sustainable energy development: A multivariate cointegration and causality analysis from Tunisian road transport sector. *Renew. Sustain. Energy Rev.* **2013**, *25*, 34–43. [CrossRef]
40. Eleri, E.O. The energy sector in southern Africa: A preliminary survey of post-apartheid challenges. *Energy Policy* **1996**, *24*, 113–123. [CrossRef]
41. Dasappa, S. Potential of biomass energy for electricity generation in sub-Saharan Africa. *Energy Sustain. Dev.* **2011**, *15*, 203–213. [CrossRef]
42. Sims, R.; Taylor, M.; Saddler, J.; Mabee, W. *From 1st- to 2nd-Generation Biofuel Technologies: An Overview of Current Industry and RD&D Activities*; International Energy Agency (IEA): Paris, France, 2008; pp. 16–20.
43. Barros-Rios, J.; Romani, A.; Peleteiro, S.; Garrote, G.; Ordas, B. Second-generation bioethanol of hydrothermally pretreated stover biomass from maize genotypes. *Biomass Bioenergy* **2016**, *90*, 42–49. [CrossRef]
44. Suganya, T.; Varman, M.; Masjuki, H.H.; Renganathan, S. Macroalgae and microalgae as a potential source for commercial applications along with biofuels production: A biorefinery approach. *Renew. Sustain. Energy Rev.* **2016**, *55*, 909–941. [CrossRef]
45. Jumbe, C.B.L.; Msiska, F.B.M.; Madjera, M. Biofuels development in Sub-Saharan Africa: Are the policies conducive? *Energy Policy* **2009**, *37*, 4980–4986. [CrossRef]
46. United States Energy Information Administration (EIA). *International Energy Statistics*; US-EIA: Washington, DC, USA, 2012.
47. Schreiner, B.; Baleta, H. Broadening the Lens: A Regional Perspective on Water, Food and Energy Integration in SADC. *Aquat. Procedia* **2015**, *5*, 90–103. [CrossRef]
48. Sparks, D.; Madhlopa, A.; Keen, S.; Moorlach, M.; Dane, A.; Krog, P.; Dlamini, T. Renewable energy choices and their water requirements in South Africa. *J. Energy S. Afr.* **2014**, *25*, 80–92.
49. Dekker, J.; Nthontho, M.; Chowdhury, S.; Chowdhury, S.P. Economic analysis of PV/diesel hybrid power systems in different climatic zones of South Africa. *Int. J. Electr. Power Energy Syst.* **2012**, *40*, 104–112. [CrossRef]

50. Luxande, A.; Schutze, E. *Mid-Term Review of the SADC Renewable Energy Support Programme: A Report*; CAMCO Clean Energy: Pretoria, South Africa, 2012.
51. Department of Energy (DoE). *Integrated Resource Plan for Electricity 2010–2030*; Department of Energy: Pretoria, South Africa, 2012.
52. Walwyn, D.R.; Brent, A.C. Renewable energy gathers steam in South Africa. *Renew. Sustain. Energy Rev.* **2015**, *41*, 390–401. [CrossRef]
53. Sebitosi, A.B.; Okou, R. Re-thinking the power transmission model for sub-Saharan Africa. *Energy Policy* **2010**, *38*, 1448–1454. [CrossRef]
54. South African Power Pool (SAPP). *SAPP Annual Report*; SAPP: Harare, Zimbabwe, 2015.
55. Madhlopa, A.; Sparks, D.; Keen, S.; Moorlach, M.; Krog, P.; Dlamini, T. Optimization of a PV-wind hybrid system under limited water resources. *Renew. Sustain. Energy Rev.* **2015**, *47*, 324–331. [CrossRef]
56. Mandelli, S.; Barbieri, J.; Mattarolo, L.; Colombo, E. Sustainable energy in Africa: A comprehensive data and policies review. *Renew. Sustain. Energy Rev.* **2014**, *37*, 656–686. [CrossRef]
57. South African Power Pool (SAPP). *SAPP Statistics 2014*; SAPP: Harare, Zimbabwe, 2014.
58. Fritzmann, C.; Löwenberg, J.; Wintgens, T.; Melin, T. State-of-the-art of reverse osmosis desalination. *Desalination* **2007**, *216*, 1–76. [CrossRef]
59. Gulati, M.; Jacobs, I.; Jooste, A.; Naidoo, D.; Fakir, S. The Water–energy-food Security Nexus: Challenges and opportunities for food security in South Africa. *Aquat. Procedia* **2013**, *1*, 150–164. [CrossRef]
60. United Nations World Water Assessment Programme (WWAP). *The United Nations World Water Development Report*; WWAP: Paris, France, 2014.
61. New Partnership for Africa's Development (NEPAD). *Water in Africa: Management Options to Enhance Survival and Growth*; NEPAD: Addis Ababa, Ethiopia, 2006.