Blue Energy from Southern African Water Bodies: State-of-the-art, Challenges and Opportunities

Kaniki Tumba

Abstract—In Southern Africa, the energy sector is characterised by the extensive use of coal fired power plant as well as fossil fuels. This causes environmental pollution and increased greenhouse gas emissions thereby contributing to global warming. Although solar and wind energy have emerged as major contributors to the renewable energy mix in Southern Africa, it is still necessary to diversify energy sources, with emphasis on those offering advantages beyond efficiency and renewability. Salinity gradient energy (SGE) or blue energy is one such form. Blue energy of which reverse electrodialysis (RED) represents the most attractive form is a type of marine or oceanic energy generated by mixing two water streams of different salinities. It involves the use of ion exchange membranes in an electrochemical process. The aim of the present article is to evaluate progress made in Southern Africa in the production of electricity by reverse electrodialysis. After providing some background information on RED, challenges and opportunities associated with future electricity generation in Southern Africa by RED at industrial scale were also examined. The findings revealed the inexistence of a single RED-based power plant in Southern Africa. However, it is important to mention the huge potential in blue energy provided by the numerous rivers, streams, lakes and oceans found in this region. It is concluded that future studies should focus on applying the technology to the region by training a critical mass of local researchers, a more accurate evaluation of the potential of each country to use blue energy and innovation related to the use of blue power as well as the socio-economic evaluation of integrating electricity production with some processes such as wastewater treatment, desalination and sodium hydroxide production.

Keywords—Renewable energy, blue energy, reverse electrodialysis, water, Southern Africa.

I. INTRODUCTION

Southern African energy supply to industries and households is dominated by the combustion of coal and petroleum-derived fuels. As an illustration, it is estimated that more than 90% of electricity is generated by coal-fired thermal power stations in South Africa [1].

The combustion of fossil fuels, i.e. coal and crude oil-based fuels, leads to considerable environmental pollution due to high emissions of greenhouse gases which accelerate climate change towards devastating effects in the long-run. Pollution and exhaustibility of fossil fuels prompted the commitment of all Southern African governments towards renewable and efficient sources of energy, ensuring the reduction of disastrous environmental, economic, and social impacts associated with these sources of Energy.

Solar and wind energies which emerge as the major contributors to the South African renewable energy landscape would not be able to meet the Southern African energy demand in the context of total decarbonisation of the power sector. Hence, there is need to diversify the sources of energy with emphasis on those providing some other advantages beyond efficiency and renewability. One such renewable energy is salinity gradient energy (SGE) also termed as blue energy, a type of ocean or marine energy that can be practically harnessed at river mouths where freshwater and sea saltwater meet. This article reviews the advances made in the use of Reverse Electrodialysis, the most promising process for blue energy, in Southern Africa with the aim of sparking more interest from researchers, industries and businesses in this type of ocean energy having a lot to offer to this geographical region. After a brief introduction this article summarises essential information on the Southern African region as well as blue energy. This is followed by advances (present and future) of the use of RED in Southern Africa before addressing challenges and opportunities.

II. SOUTHERN AFRICA OVERVIEW

Southern Africa is a vast region covering all African countries whose territories are entirely below the equatorial forest. However, in this article, the Democratic Republic of Congo (DRC) is added to consider all countries comprising the Southern African Development Community whose members are Angola, Botswana, the Comoros, the Democratic Republic of Congo, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, South Africa, Zambia, and Zimbabwe (Figure 1). The 16 countries represent an
8 million km² large region with 400 million inhabitants, hosting major rivers and two oceans, i.e., the Indian and Atlantic oceans. As shown in Table 1, there are altogether 15 transboundary river basins in Southern Africa. A wide range of energy sources are used in Southern Africa. However, there is a considerable reliance of fossil fuel. The total installed capacity amounts to 72963.3 MW while the average electrification rate (access to electricity) is 48% [2].

TABLE I
River basins in Southern Africa [3].

<table>
<thead>
<tr>
<th>River</th>
<th>Basin Area (km²)</th>
<th>River Length (km)</th>
<th>Riparian States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buzi</td>
<td>31 000</td>
<td>250</td>
<td>Zimbabwe, Mozambique</td>
</tr>
<tr>
<td>Congo</td>
<td>3 730 470</td>
<td>4 700</td>
<td>Angola, Burundi, Rwanda, Central African Republic, Tanzania, Congo, Cameroon, DR Congo, Zambia</td>
</tr>
<tr>
<td>Cuvelai</td>
<td>100 000</td>
<td>430</td>
<td>Angola, Namibia</td>
</tr>
<tr>
<td>Incomati</td>
<td>49 965</td>
<td>480</td>
<td>South Africa, Swaziland, Mozambique</td>
</tr>
<tr>
<td>Kunene</td>
<td>106 500</td>
<td>1 050</td>
<td>Angola, Namibia</td>
</tr>
<tr>
<td>Limpopo</td>
<td>408 000</td>
<td>1 750</td>
<td>Botswana, South Africa, Mozambique</td>
</tr>
<tr>
<td>Maputo-Usutu-Pongola</td>
<td>32 000</td>
<td>380</td>
<td>South Africa, Swaziland, Mozambique</td>
</tr>
<tr>
<td>Nile</td>
<td>3 254 555</td>
<td>6 700</td>
<td>Tanzania, Burundi, Rwanda, Kenya, Uganda, D R Congo, Ethiopia, Sudan, Egypt</td>
</tr>
<tr>
<td>Okavango</td>
<td>530 000</td>
<td>1 100</td>
<td>Angola, Namibia, Botswana</td>
</tr>
<tr>
<td>Orange-Senqu</td>
<td>721 000</td>
<td>2 300</td>
<td>Lesotho, South Africa, Botswana, Namibia</td>
</tr>
<tr>
<td>Pingwe</td>
<td>32 500</td>
<td>300</td>
<td>Zimbabwe, Mozambique</td>
</tr>
<tr>
<td>Ruvuma</td>
<td>155 500</td>
<td>800</td>
<td>Tanzania, Malawi, Mozambique</td>
</tr>
<tr>
<td>Saver/Sabi</td>
<td>106 420</td>
<td>740</td>
<td>Zimbabwe, Mozambique</td>
</tr>
<tr>
<td>Umbeluzi</td>
<td>5 500</td>
<td>200</td>
<td>Swaziland, Mozambique</td>
</tr>
<tr>
<td>Zambezi</td>
<td>1 390 000</td>
<td>2 690</td>
<td>Angola, Namibia, Botswana, Zimbabwe, Zambia, Malawi, Tanzania, Mozambique</td>
</tr>
</tbody>
</table>

Fig 1 Southern African countries [3].

III. BLUE ENERGY OVERVIEW
Pressure retarded osmosis (PRO) and Reverse Electrodialysis (RED) are the most realistic processes used to harness energy resulting from mixing two streams having different salinities such as river (fresh) water and sea salt water [4] [5]. Osmosis is the flow of solvent (pure water) from a low concentration solution to a high concentration solution through a selective, semi-permeable membrane. In PRO plants, this freshwater flow leads to high-pressure and high-water level on the concentrated solution compartment which is used to act on a turbine and produce electricity [6].

Electrodialysis refers to the controlled migration of ions comprising the solute through a selective membrane. A Reverse Electrodialysis (RED) set up allows direct electricity generation using ion exchange membranes and a set of electrodes [7]. A series of anion and cation exchange membranes are placed in an alternating pattern between an anode and a cathode. Freshwater and sea water are allowed to flow in the compartments between the membranes. A voltage is generated across each membrane pair due to the chemical potential difference resulting from the differences in salinity. The overall electric potential difference between the outer compartments of the membrane stack is the sum of the potential differences over each membrane. The low salt concentration feed (fresh water) and high concentration feed (seawater) are combined to yield electricity and two outlet streams whose concentrations lie between those of the inlet flows. These waste streams can be conveyed back to the sea or directed towards table salt production fields [4-5, 7].

Energy generation cost ($ 0.1/kWh for RED and $ 0.065 to $ 0.13 for PRO) and energy conversion efficiency (50 % to 70 % for RED and 40 %) of salinity gradient power plants are close to those usually reported for wind energy while they remain more attractive than those associated with solar energy. However, predictability is the major advantage of salinity gradient energy as compared to wind and solar energies which are highly weather-dependent.

Moreover, blue energy has the potential to solve some problems experienced by seawater desalination plants implemented in South Africa, i.e., brine management and economic non-viability. This can be made possible by coupling salinity gradient power plants with desalination plants [6]. In addition, through RED, municipality as well as industrial wastewaters, can be used to produce electricity. Early studies established through experimental investigations the effect of various parameters on RED stack performance. It was found that power density increases with increasing inlet stream flow rates. However, a plateau corresponding to the optimum flow rate has been consistently reported by many researchers. A linear increase in power density was observed as a result of temperature increase. This has been attributed to the positive effect of temperature on both the conductivity of solutions and ions mobility. Salinity gradients and the number of membrane pairs also emerged as important parameters of RED [6], both having a positive effect on energy production. The influence of stack size and membrane type on power density, thermodynamic efficiency and energy efficiency was investigated by many researchers.
microbial matter represents a major challenge in the use of reverse electrodialysis, contributing to low efficiencies, and high overall costs. These drawbacks are currently addressed through numerous studies aimed at developing more resistant and durable membranes while limiting fouling risks.

Process modelling and optimization are regarded as means to ensure efficient use of materials and minimize energy requirements. Optimized systems will position RED as one of the most attractive processes for energy generation both in urban and rural areas.

Rural areas which are characterised by low electricity access rates in Southern Africa can benefit from this technology without any additional stress on water resources. In effect, rural areas’ economy heavily relies on agriculture and livestock which are water intensive. However, blue energy through reverse electrodialysis uses discharged water after it has served for various purposes in communities. Therefore, no concern can be raised over negative interference with socio-economic activities requiring water in rural communities when blue energy is adopted.

Blue Energy is a freshly introduced area of research not only in Southern Africa, but also in the whole Africa. No pilot unit has been built as African researchers are doing their first steps in the field. In fact, Mangosuthu University of Technology is the only African institution undertaking research related to blue energy which is funded by the National Research Foundation of South Africa with the aim of building a pilot power plant based on reverse electrodialysis in Durban area. Southern Africa can become a blue energy hub in the continent when the following opportunities are considered:

- Political will to reduce greenhouse gas emissions.
- Presence of many water bodies: streams, rivers, lakes, oceans.
- Potential for a wide range of innovations in relation to processes such as:
  - Combined wastewater and electricity generation in mines, both operational and abandoned mines,
  - Coupling desalination and reverse electrodialysis
  - Coupling bleach (sodium hydroxide) manufacturing and reverse electrodialysis

However, challenges have been identified as:

- lack of data which can be used in simulations (flow rates, salinity, water availability…)
- small number of researchers involved in the field
- lack of adequate funding in most Southern African countries

#### IV. STATE-OF-THE-ART, CHALLENGES AND OPPORTUNITIES

There are less than five operational salinity gradient power plants in the world. Hence, salinity gradient power generation is still at its infancy. Nevertheless, there are reports of ongoing projects in many coastal countries, including pilot power stations already built in Italy, China, Norway, and the Netherlands, with installed capacities ranging from 50 to 700 kW [5].

Recent investigations identified two major obstacles that hinder the widespread implementation of blue energy. These include the inadequacy of membranes as well as high operating costs in some locations which are currently addressed by researchers through experimental and modelling studies [14]. Understandably, research is going on in the following areas:

- Development of robust membranes,
- Process modelling and optimisation
- Design of autonomous units for landlocked regions.

The presence of foulants such as colloids, inorganic compounds, organic compounds, microorganisms, and
V. CONCLUSION

After examining the situation regarding blue energy in Southern Africa, it emerges that:

- The DRC has the greatest potential in terms of blue energy in the region as it is well positioned to play a major role in changes that can emanate from blue energy integration into the Southern African energy mix; there is more than Inga III,
- Southern Africa is likely to claim the largest share of blue energy potential among all the major African regions
- Blue energy adoption can overturn energy challenges in the region
- There is need for new hands and new brains to advance this area of research in Southern Africa,
- There is room for plenty of innovation through RED research

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REFERENCES