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

Kaniki Tumba[1]

***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

Kaniki Tumba is affiliated with the Thermodynamics-Materials-Separations Research Group, in the Department of Chemical Engineering at Mangosuthu University of Technology in Durban, South Africa.

https://doi.org/10.17758/IICBE3.C0322269

8 million km^2 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].

River	Basin Area (km²)	River Length (km)	Riparian States
Buzi	31 000	250	Zimbabwe, Mozambique
Congo	3 730 470	4 700	Angola, Burundi, Rwanda, Central African Republic, Tanzania, Congo, Cameroon, DR Congo, Zambia
Cuvelai	100 000	430	Angola, Namibia
Incomati	49 965	480	South Africa, Swaziland, Mozambique
Kunene	106 500	1 050	Angola, Namibia
Limpopo	408 000	1 750	Botswana, South Africa, Zimbabwe, Mozambique
Maputo-Usutu-Pongola	32 000	380	South Africa, Swaziland, Mozambique
Nile	3 254 555	6 700	Tanzania, Burundi, Rwanda, Kenya, Uganda, D R Congo, Eritrea, Ethiopia, Sudan, Egypt
Okavango	530 000	1 100	Angola, Namibia, Zimbabwe, Botswana
Orange-Senqu	721 000	2 300	Lesotho, South Africa, Bostwana, Namibia
Pungwe	32 500	300	Zimbabwe, Mozambique
Ruvuma	155 500	800	Tanzania, Malawi, Mozambique
Save/Sabi	106 420	740	Zimbabwe, Mozambique
Umbeluzi	5 500	200	Swaziland, Mozambique
Zambezi	1 390 000	2 650	Angola, Namibia, Botswana, Zimbabwe, Zambia, Malawi, Tanzania, Mozambique

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 difference 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

[8]. Through their study, the residence time was identified as the predominant parameter for the comparison of differently sized stacks as well as upscaling RED stacks from laboratory data. The merit of this study is to have provided guidelines for building pilot or industrial RED installations based on comprehensive criteria which included not only power density but also gross and thermodynamic efficiencies.

The aforementioned experimental studies were instrumental in deriving models for simulation purposes. The earliest modelling studies related to RED considered the theoretical estimation of output electric variables such as voltage and power density to roughly approximate the technical feasibility of power generation. In the very first comprehensive study, Lacy was successful in relating the cell pair voltage to the potential drops through solutions, boundary layers and ionic exchange membrane features [9]. This model was modified by Brauns [10] who showed that the performance of the RED stack could be considerably enhanced by using very thin ion exchange membranes up to less than 10 µm. One of the rare models incorporating the non-ideal behaviour of ionic exchange membranes is that developed by Veerman et al [11] and further improved by Tedesco et al [12]. The latter researchers examined a wider concentration range in the derived model. Finally, Tedesco et al [13] proposed a more comprehensive model for the RED process using sea or brackish water and concentrated brine as feed solutions. The careful use of thermodynamic models for property prediction and sound incorporation of Computational Fluid Dynamics are the major strengths of this model. Although interesting advances have been achieved in RED process modelling, there is still need for more accurate and more realistic models to inform RED scaling up and widespread industrial implementation.

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 on-going 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 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

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

ACKNOWLEDGMENT

This work is financially supported by the National Research Foundation of South Africa.

Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, “Electron spectroscopy studies on magneto-optical media and plastic substrate interfaces(Translation Journals style),” *IEEE Transl. J. Magn.Jpn.*, vol. 2, Aug. 1987, pp. 740–741

REFERENCES

[1] B.O. Oboirien, B.C. North, and T. Kleyn, “Techno-economic assessments of oxy-fuel technology for South African coal-fired power stations”, Energy, vol. 66, pp.550-555, 2014. https://doi.org/10.1016/j.energy.2013.12.032

[2] https://www.sadc.int. Accessed on 20th February 2022

[3] https://www.limpopo.riverawarenesskit.org/. Accessed on 20th February 2022

[4] A. Hussain, S. M. Arif, and M Aslam, “Emerging renewable and sustainable energy technologies: State of the art”, *Renewable and Sustainable Energy Reviews*, vol. 71, pp. 12-28, 2017. https://doi.org/10.1016/j.rser.2016.12.033

[5] Cipollina, A., and Micale, G. eds. "Sustainable energy from salinity gradients." (2016).

[6] F. Helfer, O. Sahin, C. Lemckert, and Y. Anissimov, “Salinity gradient energy: a new source of renewable energy for Australia”, in Proc. *8th International Conference of the European Water Resources Association*, 2013.

[7] P. Długołęcki, K. Nymeijer, S. Metz, and M. Wessling, “Current status of ion exchange membranes for power generation from salinity gradients”, *Journal of Membrane Science*, vol. 319, pp. 214-222, 2008. https://doi.org/10.1016/j.memsci.2008.03.037

[8] J. Moreno, S. Grasman, R. van Engelen, and K. Nijmeijer, “Upscaling reverse electrodialysis”, *Environmental science & technology*, vol. 52(18), pp10856-10863, 2018. https://doi.org/10.1021/acs.est.8b01886

[9] R.E. Lacey, Lacey, R. E. "Energy by reverse electrodialysis." *Ocean engineering*, vol. 7 (1) pp 1-47, 1980. https://doi.org/10.1016/0029-8018(80)90030-X

[10] Brauns, E., “Salinity gradient power by reverse electrodialysis: effect of model parameters on electrical power output”, *Desalination*, vol. 237 (1-3), pp. 378-391, 2009. https://doi.org/10.1016/j.desal.2008.10.003

[11] J. Veerman, M. Saakes, S.J. Metz, and G.J. Harmsen, “Reverse electrodialysis: A validated process model for design and optimization”, *Chemical Engineering Journal*, vol. 166 (1), pp. 256-268, 2011. https://doi.org/10.1016/j.cej.2010.10.071

[12] M. Tedesco, A. Cipollina, A. Tamburini, W. van Baak, and G. Micale, “Modelling the Reverse Electrodialysis process with seawater and concentrated brines”, *Desalination and Water Treatment*, vol. 49(1-3), 404-424, 2012. https://doi.org/10.1080/19443994.2012.699355

[13] M. Tedesco, A. Cipollina, A. Tamburini, I.D.L. Bogle, and G. Micale, “A simulation tool for analysis and design of reverse electrodialysis using concentrated brines”, *Chemical Engineering Research and Design*, vol. 93, pp. 441-456, 2015. https://doi.org/10.1016/j.cherd.2014.05.009

[14] C.R. Merz, W.A. Moreno, M. Barger, and S.M. Lipka, “Salinity gradient power (SGP): A developmental roadmap covering existing generation technologies and recent investigative results into the feasibility of bipolar membrane-based salinity gradient power generation”, *Technology & Innovation*, 14 (3-4), pp. 249-275, 2012. https://doi.org/10.3727/194982412X13500042168857