WIND ENERGY DEVELOPMENT IN SUB-SAHARAN AFRICA: APPLICATION OF THE SATSA FRAMEWORK

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ABSTRACT

There is a need for a framework that can be applied to wind energy developments in the sub-Saharan African (SSA) context that will facilitate technology-sustainable assessments to promote wind energy. This paper applies such a framework to potential wind energy developments in Namibia and Mozambique. In addition, the use of a system dynamics approach allows for wind turbine and power considerations to be adequately integrated into the application of the framework. The study applies the framework to both these countries to develop an outlook for potential wind energy developments. This results in the identification of key success factors.

OPSOMMING

Hierdie artikel identifiseer ’n behoefte aan ’n stelsel raamwerk met toepassing in wind energie stelsels in Afrika suid van die Sahara. Sodanige raamwerk moet volhoubaar binne konteks toegepas word. Hierdie studie fokus op sodanige toepassing in Namibië en Mosambiek. Behalwe vir die toepassing van sodanige raamwerk, maak hierdie navorsing ook gebruik van ’n stelsel dinamika benadering. Hierdie tegniek is veral van hulp tydens die integrasie van wind turbine en energie oorwegings as deel van ’n stelsel raamwerk. Hierdie studie fokus ook op die toepassing van sodanige raamwerk in Namibië en Mosambiek om daardeur ’n wetenskaplike oorsig van wind energie potensiaal aldaar te skets. Hieruit volg die identifisering van sleutel sukses faktore relevant tot wind energie stelsels.

1 INTRODUCTION

The global electricity scenario is evolving at a rapid rate, with a movement away from environmentally unfriendly fossil-based electricity-producing mechanisms to those of cleaner renewable energy, thus allowing various large greenhouse gas-emitting countries to reduce their carbon footprint [1]. In the drive towards cleaner energy, technology assessments (TA) have provided a useful tool in aiding and supporting decision-making about a country’s choice of the renewable energy technology strategy being undertaken to supplement conventional electricity production schemes [2]. According to recently conducted research, renewable energy and, in particular, wind energy within the sub-Saharan African (SSA) context is underdeveloped, with only 43MW of a potential 1GW being used [3]. There is therefore a need for a framework that supports policy and decision-making in choosing particular technology options that are applicable to the context and needs of specific countries [2].

A critical review of technology assessments conducted by Tran and Daim [4] further illustrates that existing methodologies do not provide a guiding mechanism for renewable energy developments — they lack the incorporation of, and application to, practical scenarios that consider sustainable development as a vital part of technology decision-making. The need for technology assessments to provide a multi-faceted paradigm has been addressed through the incorporation of a technological, sustainable, and dynamic systems approach created by Musango and Brent [2]. This approach used a systems approach to technology sustainability assessment (SATSA), which provided a key guiding mechanism for renewable energy developments within the sustainable development context.

This research endeavour aimed to address the need for further knowledge about the applicability of technology assessments to practical scenarios though the use — and incorporation — of sustainable development and system dynamics. This study built new knowledge by applying the proposed SATSA framework of Musango and Brent [2] to wind energy and its underdevelopment in the SSA context, as pointed out by Mukasa, Mutambatsere, Arvanitis and Triki [3]. Furthermore, the study provided further insight into the practical applicability of this tool to assist policy-making in providing the best technology options for various countries in the context of sub-Saharan Africa (SSA).

To address these points, the study adopted a structured approach that incorporated the following areas.

1.1 Wind energy

Due to environmentally friendly practices and the drive to reduce carbon dioxide emissions, renewable energy is playing an ever-increasing role in the energy sector. In order to reduce environmental risks and improve economic and social development, wind energy in particular is playing an important role in facilitating this aim by providing a clean renewable source of energy [5]. Despite varying opinions, wind energy is largely recognised as the cleanest energy producing system from an environmental perspective. But it has faced challenges in respect of its sustainability, as pointed out by Tejeda and Ferreira [6]. These authors [6] substantiate the importance of using system dynamics to facilitate the development of wind energy developments in the SSA context, which ultimately provide for a holistic view of energy developments and thus promote renewable energy developments and policy-making.

1.2 Technology assessments and sustainability

Technology assessments (TAs) have numerous applications, and can be used in various applications to guide decision-making about technological endeavours. According to Banta [7], technology assessments can be defined as

"….a form of policy research that examines short- and long-term consequences (for example, societal, economic, ethical, legal) of the application of technology."

Tejeda and Ferreira [6], citing (adapted for an energy system) from The World Commission on Environment and Development (WCED), define 'sustainable development' (SD) as

"an energy system that meets the needs of the present without compromising the ability of future generations to meet their own needs."

The incorporation of SD in TAs can provide an approach to assessing how wind energy can be promoted and advanced in the SSA context.

1.3 SATSA framework and system dynamics

The SATSA framework developed by Musango, Brent, Amigun, Pretorius and Müller [8] is a proposed framework for assessing renewable energy developments through the use and consideration of technology, sustainability, and system dynamics. To provide a framework that could be applied to the renewable energy scenario, the SATSA framework incorporates the considerations made by the Millennium Institute, which centres energy development on society, the environment, and the economy. The SATSA framework, in its most basic form, is illustrated in Figure 1.

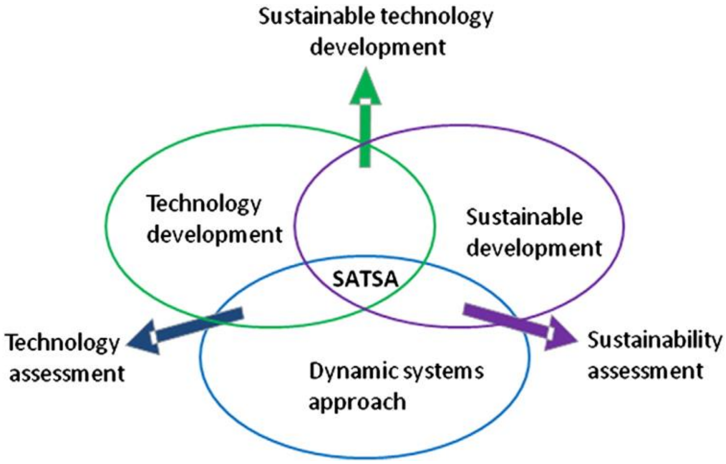


Figure 1: SATSA framework (Source: Musango *et al*. [8])

Seel [9] further states:

"System dynamics refers to studying complex systems by applying feedback loops. Stocks and flows are the basic building blocks of system dynamic models. They help describe how a system is connected by feedback loops which create the nonlinearity found so frequently in modern day problems".

Thus the application of a dynamic systems approach can be used to simplify and allow for easier exploration of complex problems that, in turn, aid in applying the SATSA approach to potential wind energy developments.

2 RESEARCH OBJECTIVES AND APPROACH

Having confirmed that an appropriate framework enhances decision-making about policy-making and national strategic energy goals, we can show that research needs to build on and apply such a framework to wind energy developments in the SSA context. In order to achieve this, the study addressed the following objectives: (i) Apply a systems approach to the technology sustainability assessment (SATSA) framework to wind development in sub-Saharan Africa; (ii) Create a systems dynamic model for wind energy in sub-Saharan Africa through the use of quantitative modelling; and (iii) Provide a framework for assessing wind energy potential in sub-Saharan African countries.

Investigating the application of a framework within SSA and linking it to the renewable energy sector entailed using the SATSA framework and, in particular, applying it to wind energy developments in the SSA context. To achieve this, our methodology used three key areas encompassing the framework: technology development, sustainable development, and system dynamics. These three overarching areas provide the foundation for the analytical framework adopted by the study, as seen in the figure below.

For renewable energy potential to be realised effectively in SSA, there is a strong need for policy frameworks that promote and guide energy developments, as pointed out by Welsch, Bazilian, Howells, Divan, Elzinga, Strbac, Jones, Keane, Gielen, Balijepalli, Brew-Hammond and Yumkella [10]. Such a need requires that the SATSA approach be adopted and used in policy development and technology assessments, thereby helping to promote informed decision-making with regard to sustainable renewable developments. Bazilian, Nussbaumer, Rogner, Brew-Hammond, Foster, Pachauri, Williams, Howells, Niyongabo, Musaba, Gallachóir, Radka and Kammen [11] further emphasise the need for an adaptive framework by highlighting the fact that insufficient planning, lack of policy to drive decision–making, and misguided investments have crippled energy developments in the SSA context.

The application of the framework/methodology adopted by this research included an analysis of wind energy requirements, available resources, and key factors associated with promoting these developments. This is illustrated in Figure 3.

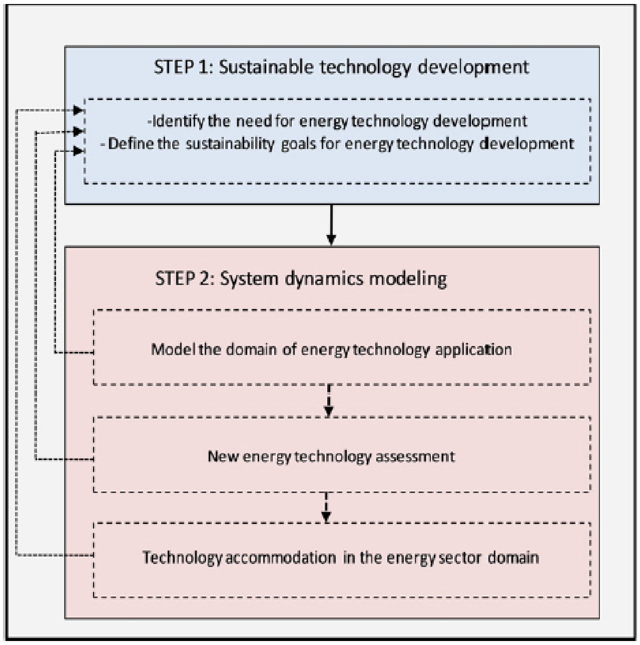


Figure 2: Systems approach to technology sustainability assessment (SATSA) (Source: Musango and Brent [2])

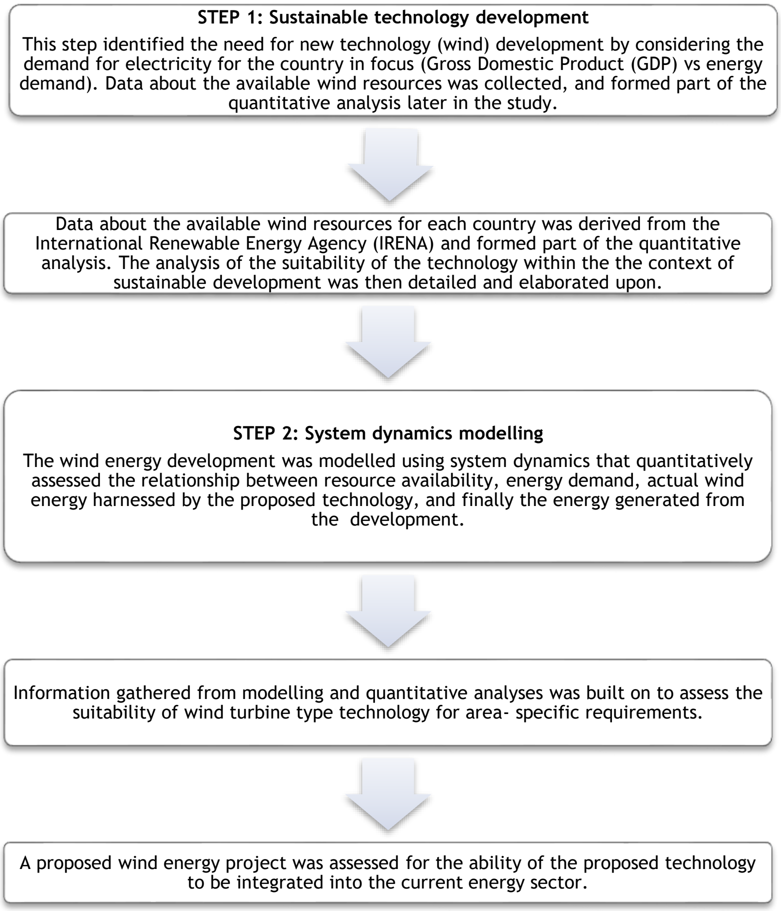


Figure 3: Research approach (Source: Authors)

Following this approach, the study raised the following questions: (a) can the SATSA framework be applied to wind energy in SSA to guide strategic energy goals? (b) What are the key success factors required to promote wind energy in SSA? and (c) How can system dynamics modelling be used as a tool in the SATSA framework to break down complex wind energy development challenges? Although the study is relevant to SSA, it is impractical to attempt to address such a large geographic region. In order to remain practical, the study instead selected two SSA countries that do offer some wind energy potential, yet are vastly underserviced by most forms of renewable energy and, in particular, wind energy. The countries selected were Namibia and Mozambique, as these are representative of most SSA countries when seen from a number of perspectives that are explained in the next section.

3 REPRESENTATIVE SSA COUNTRIES: SATSA STEP 1 RESULTS

A number of SSA countries have a vast array of traditional energy resources, with coal contributing a large portion of the energy mix [12]. According to studies conducted by the International Renewable Energy Agency (IRENA) [12], some of these countries also have extensive wind and solar energy potential, most of which is underdeveloped and contributes little to the existing energy mix. Although South Africa immediately comes to mind, it is fast addressing this aspect. South Africa is now credited with having one of the world's largest and most successful renewable energy programmes, perhaps making it a less interesting subject example for this study. Looking at the larger SSA picture, however, a number of interesting trends are apparent, as illustrated in Figure 4 below.

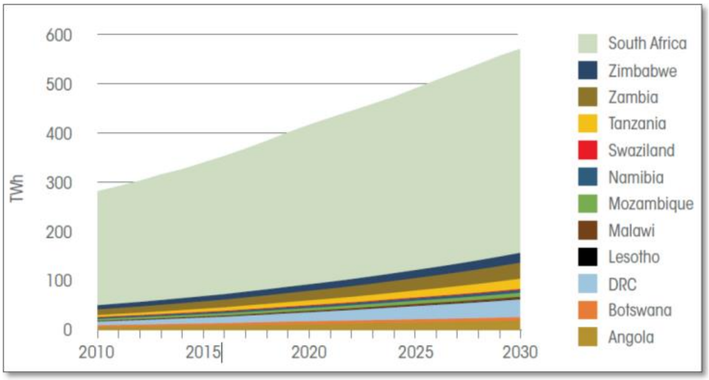


Figure 4: Predicted energy demand in Southern Africa (Source: IRENA [12]) (see online version for colour)

Further analysis suggests that, of these countries, only a relatively small number have excellent, yet underdeveloped, wind resources, mostly in their coastal regions. Selecting (Step 1, Figure 3) Namibia and Mozambique as subject countries for this study provides two rather interesting, yet challenging — from an economic and political viewpoint — case studies. Figure 5 identifies the wind resources of these two countries [13].

It is evident from Figure 5 that, for both Namibia and Mozambique, the best wind resources (not surprisingly) appear to be along their coastlines. Despite both countries not being classified as having the best wind resources in SSA [14], focusing on these countries in some detail shows why they both make suitable study subjects.

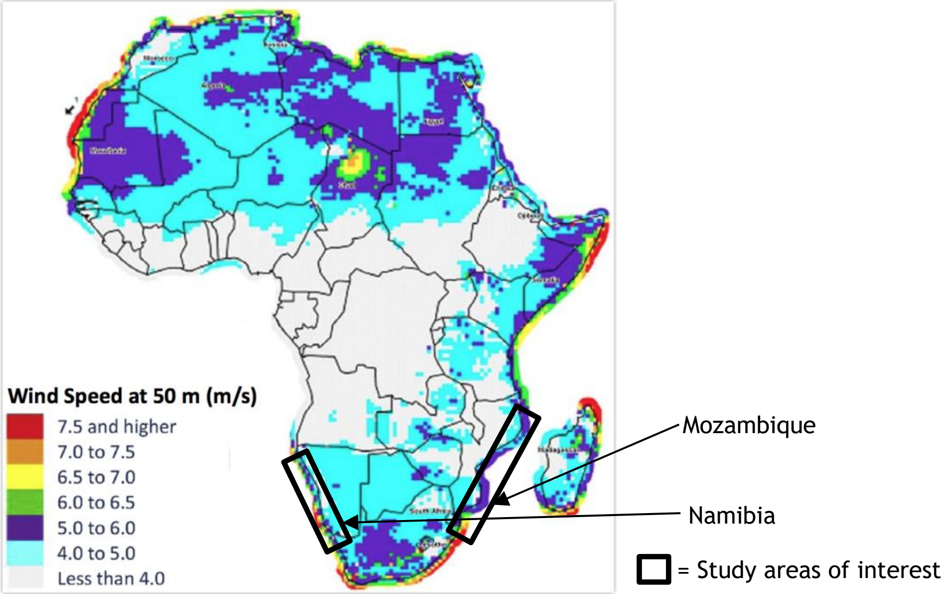


Figure 5: Elevated wind speeds across the African continent (Source: Mukasa [13]) (see online version for colour)

3.1 Namibia as case study

Namibia is located on the west coast of SSA. Oertzen [15] confirms that wind energy has promising potential in that country, making it especially attractive, since Namibia's existing conventional energy resources are unable to meet current demands. Furthermore, data adapted from Suberu, Mustafa, Bashir, Muhamad and Mokhtar [16] illustrates that, of the total population of 2.1 million, some 1.4 million have no access to electricity, meaning that a mere 0.7 million people having access to electricity. On a larger scale, work done by Onyeji, Bazilian and Nussbaumer [17] further illustrates this by pointing to a lack of access to electrical energy as high as 69 per cent in the SSA context, roughly in agreement with Suberu *et al*. [16]. In particular, the area between Luderitz and Ponoma possesses substantial wind resources, thus providing the basis for the application of the SATSA framework in this study. This area shows promising potential due to its resources and the feasibility of using grid connections that are available in the area. As well as showing good wind potential, the country shows a steadily rising gross domestic product (GDP), which, coupled with endemic energy shortages, makes Namibia an excellent country of study [18] (see Figure 6).

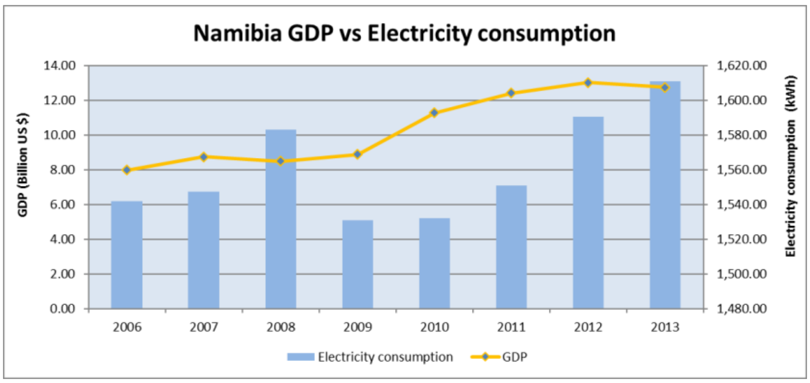


Figure 6: GDP vs Electricity consumption trend for Namibia (Data: World Bank [18])

The Namibian study area, as pointed out in Figure 6 above, was further focused on, and encompasses an area outlined by the polygon insert shown in Figure 8a. The focus area was conditioned to ensure that no less than 2500 km^2 was covered in order to provide a more accurate assessment of wind potential in the area. The wind resource assessment was conducted using the IRENA global wind atlas, which provided further data to be used in step 2 of the SATSA framework application (Figure 2). Once a polygon representing the study area had been established, the potential wind speed estimation illustrated promising signs, with average wind speeds of about 8.15 m/s.

3.2 Mozambique as case study

Mozambique's energy challenges are vast, including the need to increase energy supply to residents and to expand the energy infrastructure to meet and provide for the demands of about 60 per cent of the population who require access to energy, according to Broto, Boyd and Hammar [19]. Estimates by the World Bank [18] differ from the figures of Broto *et al* [19], with the World Bank stating [18] that almost 80 per cent of Mozambique's population have no access to electricity. But more important than the differences in absolute figures is the clear evidence that the vast majority of the country's population can be seen as energy-poor. Despite considerable wind energy supplies, weather (cyclones) and the rise and fall in costs relating to projects produce low investor confidence because of the high risks involved, even when considering off-grid approaches [20]. In order to facilitate wind energy development, a wind potential feasibility first needs to be adequately established in order to provide accurate information for informed decision-making if the country is to have any hope of enhancing its wind development prospects [21]. Like Namibia, Mozambique shows a rising GDP in conjunction with rising electricity consumption, making this country too an attractive subject for this study [18] (see Figure 7).

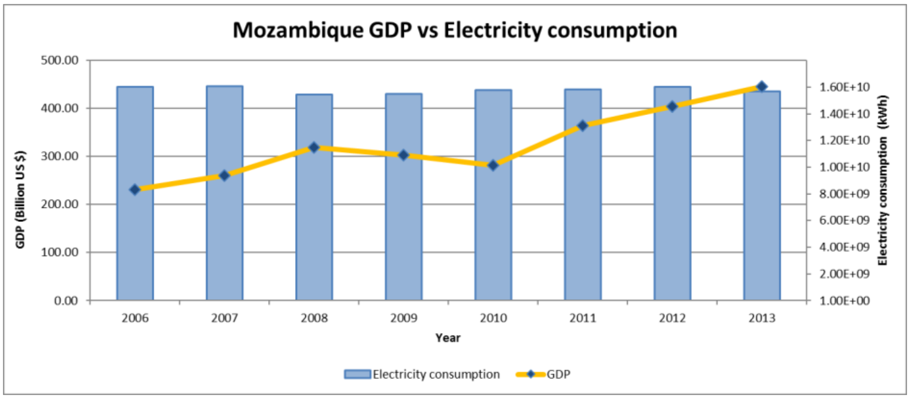


Figure 7: GDP vs Electricity consumption trend for Mozambique (Data: World Bank [18])

As in the Namibian case, a polygon highlighting and focusing on a smaller area — in this case, the greater Maputo Bay area [22] (Figure 8b) — formed the basis of the study of Mozambique. The chosen study area ensured that an area of about 2500 km^2 formed part of the data-gathering process, ensuring that data reliability did not compromise the second step of the study. The IRENA global wind atlas again provided the tool for accessing and attaining the data required for the study area. The potential for wind energy showed good signs to encourage infrastructure development, with an average wind speed of 6.88 m/s .

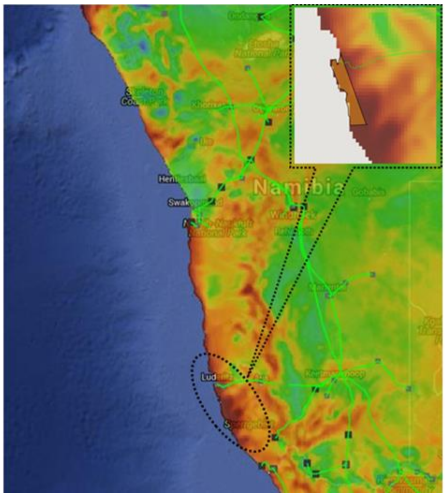


Figure 8a: Namibia study area (Source: IRENA [12]) (see online version for colour)

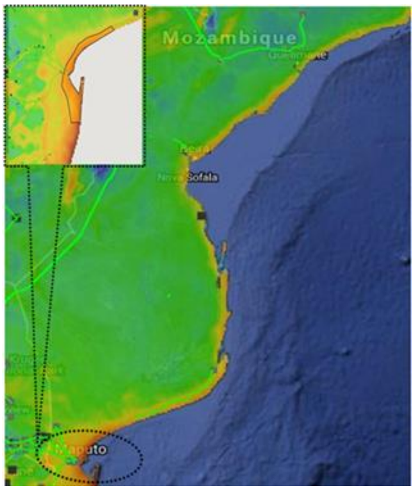
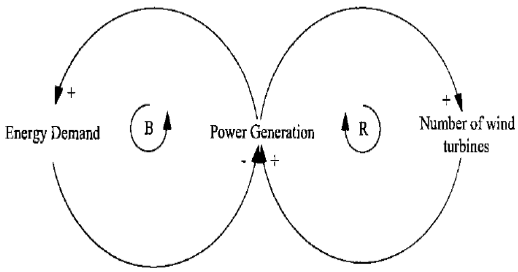


Figure 8b: Mozambique study area (Source: IRENA [22]) (see online version for colour)

4 SYSTEM DYNAMICS MODELLING: SATSA STEP 2 RESULTS

In order to create a model to address and break down a particular project's complexities, Sterman [23] developed a guideline that depends on a number of distinct steps. Goh, Lee, Chua, Goh, Kok and Teo [24] adapted this approach and applied it to renewable wind energy developments. Their study investigated the underdevelopment of wind energy in Malaysia using Vensim system dynamics modelling software to create a feedback model that illustrates relationships between various factors. Their research also investigated the feasibility of wind projects in Malaysia by applying Betz's law to wind turbine parameters using wind speed data. The application of feedback loops by Goh *et al.* [24] to determine wind energy return on investment (ROI) development parameters is illustrated below.



P = $\rho.A.v^3.C_\rho$ (Betz's law [24])

P = actual wind turbine power captured (Watt)
ρ = Betz coefficient (16/27)
A = turbine rotor swept area
v^3 = undisturbed wind speed
C_ρ = ideal power co-efficient derived from Betz coefficient (16/27)

Figure 9: Betz's law and power generation feedback loops (Source: Goh *et al.* [24])

To assess the wind energy scenario in Namibia and Mozambique, our study adopted two approaches that helped to indicate the feasibility of potential wind energy. To do this, the study first used wind data and wind speeds by applying them to Betz's law. Second, to illustrate the relationships between variables, system dynamics was applied through the use of feedback loops and causal loop diagrams (using Vensim PLE system dynamics software) effectively to investigate the underdevelopment of wind energy for the two countries being studied. Last, the application of the SATSA framework provided a holistic approach to wind energy projects in the two countries — and, by extension, to SSA.

The second step in applying the SATSA framework (Step 2 in Figure 3) covers the application of system dynamics to the technology type in focus. Step 2 encompasses adapting the turbine and system dynamics model parameters of Goh *et al.* [24] to ensure their applicability to this study. System dynamics has been used in the study to model two primary domains: electricity generated from a wind turbine, and power consumption. The system dynamics models were then applied to both Namibia and Mozambique. In both cases the study used the electricity demand sub-model proposed by Goh *et al.* [24], somewhat adapted and using relevant data sourced from the World Bank [18], for the two countries.

The system dynamics model for each country's GDP and energy growth model made use of data available from the World Bank [18]. For Mozambique, the percentage GDP growth rate over the study period was 0.73, and the GDP growth to electricity consumption ratio was 0.58. Namibia's percentage GDP growth rate over the study period was 0.48, with a GDP growth to electricity consumption ratio of 0.38. Following the analysis, both countries were found to show a positive correlation between GDP growth and power consumption growth, and their results formed input into the model (see Figures 10 and 12).

Table 1: GDP growth and electric power consumption — Mozambique (Source: World Bank [18])

Country — Mozambique (Code MOZ)								
Indicator name	2006	2007	2008	2009	2010	2011	2012	2013
GDP growth (annual %)	9.85	7.43	6.88	6.35	6.69	7.12	7.20	7.14
Electric power consumption (kWh per capita)	445.12	445.71	429.57	429.64	438.58	439.30	444.41	435.60

Table 2: GDP growth and electric power consumption — Namibia (Source: World Bank [18])

Country — Namibia (Code NAM)								
Indicator name	2006	2007	2008	2009	2010	2011	2012	2013
GDP growth (annual %)	7.07	6.62	2.65	0.30	6.04	5.09	5.06	5.68
Electric power consumption (kWh per capita)	1541.93	1547.16	1582.93	1530.88	1532.15	1550.78	1590.56	1610.85

The wind turbine power production and electricity generation system dynamics models used adapted parameters from Goh *et al.* [24] for the modelling. Power density used wind speed data from the IRENA [12], while the turbine parameters were based on those of a Vestas wind turbine (height of hub 119m and rotor diameter 112m) according to the adapted parameters mentioned above.

Table 3: Power density wind speeds — Mozambique (Source: IRENA [12])

Recorded wind speeds, Mozambique (m/s)											
7.98	7.81	7.71	7.63	7.57	7.50	7.44	7.39	7.33	7.28	7.24	7.19
7.15	7.12	7.08	7.05	7.01	6.98	6.95	6.93	6.90	6.88	6.85	6.83
6.81	6.79	6.77	6.75	6.73	6.71	6.69	6.67	6.65	6.63	6.61	6.59
6.57	6.55	6.53	6.51	6.49	6.47	6.45	6.43	6.40	6.38	6.36	6.34
6.31	6.29										

Table 4: Power density wind speeds — Namibia (Source: IRENA [12])

Recorded wind speeds, Namibia (m/s)											
8.53	8.47	8.42	8.40	8.37	8.35	8.33	8.32	8.30	8.29	8.28	8.27
8.26	8.24	8.23	8.22	8.21	8.20	8.19	8.18	8.17	8.16	8.15	8.15
8.14	8.13	8.12	8.11	8.11	8.10	8.09	8.08	8.08	8.07	8.06	8.05
8.04	8.04	8.03	8.02	8.01	8.00	7.99	7.99	7.98	7.97	7.96	7.95
7.94	7.92										

The modelling results are illustrated as follows:

- GDP and power consumption growth (Namibia and Mozambique): Figures 10 (a-c) and 12 (a-c)
- Wind turbine electricity generation (Namibia and Mozambique): Figures 11 (a, b) and 13 (a, b)

4.1 System dynamics modelling for Namibia

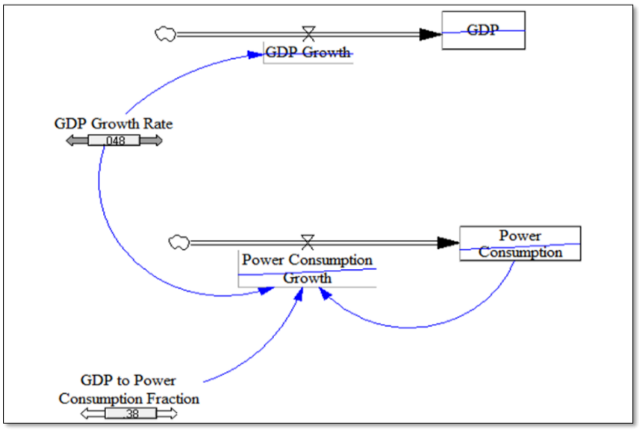


Figure 10a: System dynamics model — GDP and energy growth for Namibia (Source: Authors)

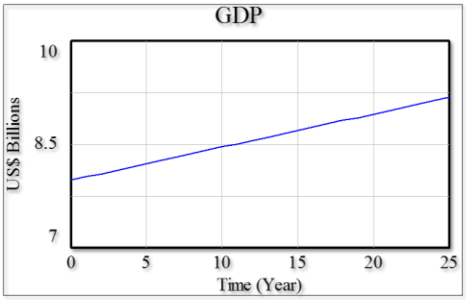


Figure 10b: GDP growth over turbine lifetime for Namibia (Source: Authors)

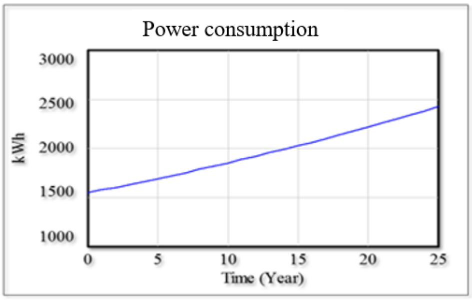


Figure 10c: Energy growth over turbine lifetime for Namibia (Source: Authors)

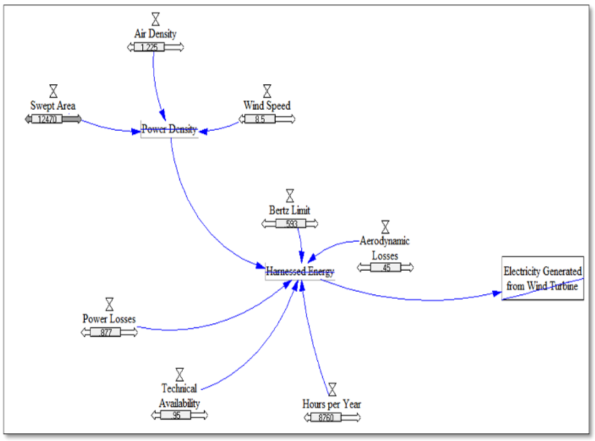


Figure 11a: Turbine power production and electricity generation for Namibia (Source: Authors)

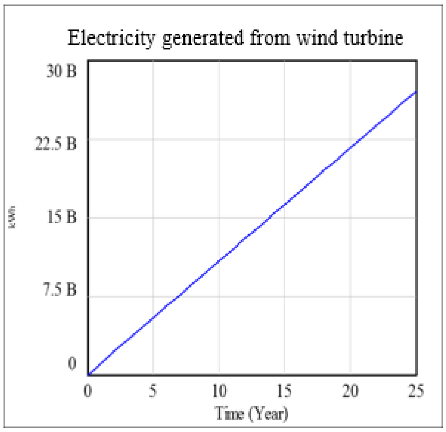


Figure 11b: Turbine electricity generation for Namibia (Source: Authors)

4.2 System dynamics modelling for Mozambique

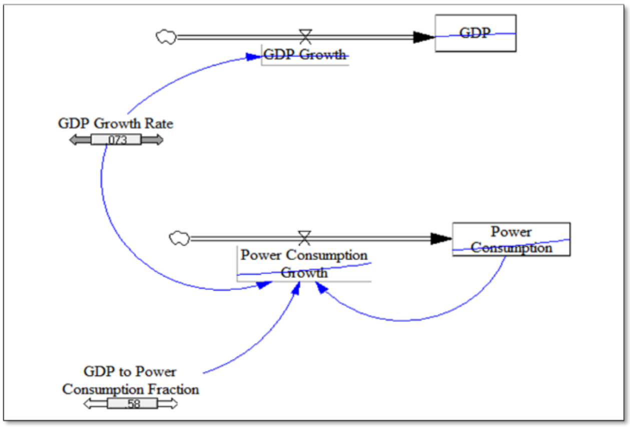


Figure 12a: System dynamics model — GDP and energy growth for Mozambique (Source: Authors)

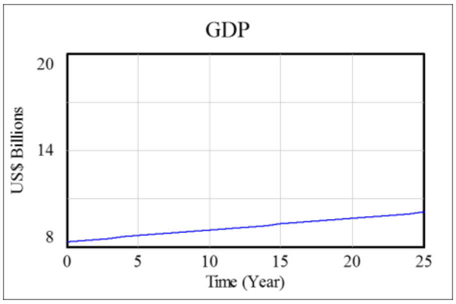


Figure 12b: GDP growth over turbine lifetime for Mozambique (Source: Authors)

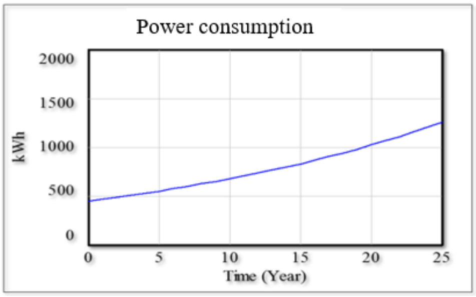


Figure 12c: Energy growth over turbine lifetime for Mozambique (Source: Authors)

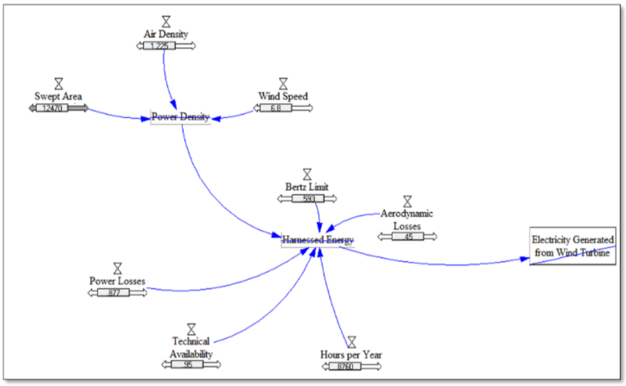


Figure 13a: Turbine power production and electricity generation for Mozambique (Source: Authors)

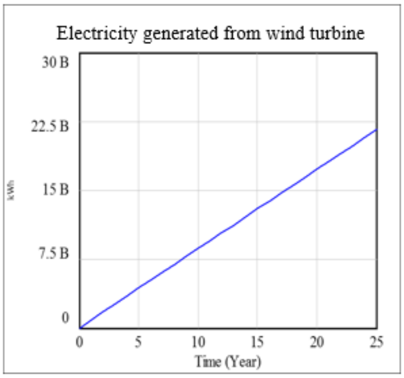


Figure 13b: Turbine electricity generation for Mozambique (Source: Authors)

4.3 Discussion of results

The application of the respective system dynamics models to Namibia and Mozambique has yielded promising potential for wind energy development. In terms of the wind energy generation from a wind turbine, both Namibia (Figure 11) and Mozambique (Figure 13) show promise. Because Namibia has significantly better wind resources, the potential electricity production over a typical turbine lifetime of 25 years is exponential. This provides encouraging investment potential for the development of prospective projects due to the stable long-term outlook for energy production in the area. Mozambique, on the other hand, despite showing lower economic growth and having lower wind resource potential, still shows that a considerable amount of energy can be produced. In terms of actual energy produced by a wind turbine, both countries show increasing and positive trends for producing electricity over the 25-year lifetime of a wind turbine.

Power consumption in relation to GDP growth in Namibia shows an almost identical relationship. Here GDP growth has also shown a rapid increase over the 25-year lifetime of a turbine. In the light of these results, it is evident that increased energy from reliable wind energy resources can play an important role in stimulating the Namibian economy.

In contrast, Mozambique has shown a steadier GDP growth output over the long term, but to maintain this requires significantly more energy. In meeting energy demand, wind energy will be able to provide a useful addition to the energy mix in this country. The addition of this resource will allow for the increased availability of energy in rural areas, and provide a basis on which to build enhanced economic growth.

In respect of wind energy developments in each of the two study subject countries, the application by this study of the SATSA framework as a guiding mechanism has proven useful. The framework provides valuable insight and structure for assessing prospective wind energy developments, confirming similar benefits found by Musango and Brent [2] in their original application of the framework in other renewable sectors, such as bio-energy. Lessons learnt from the strategy for growth of the renewable sector in South Africa, in conjunction with applying such a framework, would facilitate the successful establishment of renewable wind energy developments within the respective countries.

5 CONCLUSIONS

This paper has introduced and proposed the application of an overarching framework that combines factors such as sustainability, technology, and system dynamics to wind energy development in sub-Saharan Africa. This was achieved by exploring various aspects of the SATSA framework originally proposed by Musango and Brent [2]. The study on which this paper is based also included the electricity sub-demand model proposed by Goh *et al*. [24], which provides further detail of the relationships between wind turbines, GDP growth, and energy demand. Finally, to provide additional insight, the paper incorporated the electricity sub-demand model of *Goh et al*. [24] into the SATSA framework [2] to provide meaningful insight into their application to wind energy development in SSA by focusing on two carefully selected study subject countries that form part of SSA, *viz*. Namibia and Mozambique.

The SATSA framework implemented as part of the study is at the epicentre of technology, sustainability, and system dynamics [2], illustrated in Figure 1. Overall it is composed of two main stages (sustainable technology development and system dynamics), illustrated in Figure 2; these have been applied to the two country cases in the study. In terms of stage 2 of the SATSA framework, the system dynamics models incorporated aspects such as wind resources, energy outputs, and economic feasibility.

The framework illustrated its adaptability by incorporating a model, as well as being smoothly applied to two separate countries. The results from the application of the framework provide a basis on which to develop future energy policies. The framework is shown to be considerably adaptable to each country — in particular, the areas in these two countries that are blessed with good wind resources. The paper highlights the flexibility of the SATSA framework and shows that it can be used by developing countries as a tool for meeting their energy goals. This study has also identified key success factors, set out below, all of which are vital in ensuring a profitable and successful project.

Table 5: Key success factors for wind energy in SSA countries (Source: Authors)

Wind resource availability Technology & sustainability GDP & energy demand	Wind turbine considerations System dynamics modelling

Wind resource availability
The identification and confirmation of locations within a country for conducting an in-depth wind resource assessment is of critical importance. The assessment of the potential wind energy will also

consider supporting/surrounding energy infrastructure to aid the operation of the renewable energy facility.

Technology and sustainability
Linking technology endeavours to sustainability requirements for each country, with the inclusion of the dynamic systems approach to simplify project complexities, will aid in strategic long-term sustainable technology development.

GDP and energy demand
Economic growth requires energy as a foundation to develop, and meeting a country's energy demands is a strong driver in stimulating economic growth.

Wind turbine considerations
Carefully selecting appropriate wind turbine technologies that are applicable to each unique wind facility development is required to form part of the detailed energy assessment in order to ensure maximum energy output and efficiency.

System dynamics modelling
Merging system dynamics into technology sustainability allows the complexities of engineering systems to be broken down. This in turn facilitates improved policies and regulations to promote renewable energy developments.

This paper showed that, by integrating Musango and Brent's SATSA framework [2] and Goh *et al.*'s [24] electricity sub-demand model, and by applying the benefits of system dynamics to two disparate but relatively energy-poor countries, one can support energy policy design for SSA countries that face severe energy poverty challenges.

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