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A framework for sustainable utility scale renewable energy selection in South Africa

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A B S T R A C T

A range of varying criteria with trade-offs need consideration when selecting a suitable renewable energy technology (RET) for a specific area or location. In this study RETs in South Africa, in accordance with the national renewable energy program, were assessed to compare and highlight feasible technology options. A key objective of the study was to develop a framework that could be used to assess the various RETs at utility scale. Important criteria contributing toward the assessment of RETs were identified from literature. The criteria were used within the framework for analysis which consisted of the following factors: technical, economic, environmental, social and political. The goal of assessing RETs in South Africa was located at the top of the framework hierarchy. A total of 15 criteria were identified to use as part of the assessment. A decision-making matrix based on both qualitative and quantitative data was used to score the criteria. The RETs (solar PV, wind, CSP, hydro, biogas and biomass) in South Africa were evaluated with respect to each criterion. The study aims to contribute towards - from a developing country perspective - highlighting key barriers to technology adoption, assist in investment decisions, and ultimately contribute toward a sustainable energy infrastructure. From the analysis performed, solar PV and wind were favoured due to technology maturity and financier perception while CSP also scored favourably due to the potential to meet the baseload energy requirements. The key policy barriers identified that require attention include improved knowledge transfer and better maintenance skills across all technologies while site suitability was identified as a major barrier for hydro and biomass RETs.

1. Introduction

There is a drive toward implementing grid-connected renewable energy (RE) projects in South Africa and the Department of Energy (DOE) supports the growth of renewable energy, such as solar and wind, generally provided by Independent Power Producers (IPP's) (DOE South Africa, 2011a). However, studies suggest that investment in RETs is risky due to a degree of uncertainty associated with the technologies e.g. factors concerning the transmission of energy, economic feasibility of the project etc. (Barry et al., 2011; Masini and Menichetti, 2013; Troldborg et al., 2014; Pepito, 2003).

The objectives of this research are to, primarily develop a framework of analyses to assess RETs in South Africa (solar PV, wind, CSP, hydro, biogas and biomass), second to compare and highlight feasible technology options and third to identify specific barriers to technology adoption which will assist in decision making regarding the implementation of RETs. The research aims to contribute towards renewable energy decision making in South Africa and other developing countries (particularly in Africa) where renewable energy allocations have to be made while satisfying multiple factors, and technology feasibility may not necessarily be the major determinant. The methodology and framework used in this article is based on a mix of international and local data, both qualitative and quantitative in nature and therefore can be tailored for the conditions relevant for a specific region or country. Thus far, utility scale electricity technology implementation in South Africa has been based on political drive and cost (DOE South Africa, 2011a; Department of Energy, 2013). A more holistic approach of assessing RETs is therefore suggested, which has the potential to reduce investment risk in RETs and address the underlying barriers to adoption.

Eskom, the public utility, generates the majority of the country's energy, owns and has control of the national high-voltage

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transmission grid and is responsible for the distribution of approximately 60 percent of the electricity directly to consumers (Khan et al., 2016). In 2004, power reserve margins were on the decline which resulted in Eskom interventions. This led to Eskom initiating a $40 billion power plant construction program (Eberhard et al., 2014). A further rise in the electricity tariffs followed suit. In 2009, the South African government began investigating the option of feed-in-tariffs (FITs) for renewable energy, to expand the renewable energy supply (Eberhard et al., 2014). South Africa is abundant with renewable energy resources that can be converted to energy. As stated in the 2002 White Paper (DME South Africa, 2002), the usage of renewable energy resources did not compete in cost when compared to conventional fossil-based energy supply at that point in time. However, that situation has changed with the increased penetration and adoption of renewables (Walwyn and Brent, 2015; Msimanga and Sebitosi, 2014). Additionally, fossil fuels have an adverse impact in the form of externalities on the environment and society, which is not accounted for in the lower cost (Thopil and Pouris, 2015; Sundqvist, 2004). FITs are used by the government to accelerate private investment in renewable energy. FITs are said to represent the costs of producing a specific energy and therefore can be used to offer energy supply contracts to renewable energy producers. However, there was considerable uncertainty regarding the procurement and licensing of processes. The Department of Energy (DOE) and National Treasury concluded that FITs resulted in non-competitive procurement, which lead to the prohibition of FITs (Eberhard et al., 2014).

In 2011, the DOE indicated that a competitive bidding process for implementation of renewable energy at utility scale would be started. This resulted in the Renewable Energy Independent Power Producer Procurement Program (REIPPPP). The REIPPPP led to private sector interest and investment in grid-connected renewable energy in South Africa at prices that are competitive (Eberhard et al., 2014). The REIPPPP program forecasted the procurement of 3625 MW of power over a maximum of five tender rounds. There were caps set on the total capacity to be procured for specific technologies – wind and PV technologies had the largest allocations, whereas smaller amounts were allocated to concentrated solar, biomass, biogas, landfill gas, and hydro. The IRP update (Department of Energy, 2013) suggests continuing with the renewable bid programme for solar PV, wind and CSP, with the potential for hydropower. The REIPPPP has to date enjoyed considerable success both from a policy and implementation point of view (Eberhard and Kåberger, 2016; Eberhard and Gratwick, 2011). However, sustainable introduction on new technologies in a new context or country has to satisfy multiple criteria. Multi-criteria decision making has been used at varying levels both national (Santos et al., 2018) and regional, particularly municipal (Coban et al., 2016; Neves et al., 2018). Multi-criteria studies have also been used for energy transition planning (Trianni et al., 2014b; Ren and Dong, 2018) and technology feasibility analysis (Fozer et al., 2017).

The next section starts by performing a review of factors and criteria used to evaluate RETs. The review enables identification of the main criteria relevant for South Africa. After having identified the criteria, a methodology and framework is devised to analyse the criteria while categorising the criteria into multiple factors (or categories). The qualitative and quantitative data relevant for the criteria is collected and populated into the framework. Once the multi-criteria assessment is performed RETs are scored for each factor and policy recommendations are made. The method and framework used can be adapted for other countries in Africa and parts of the world where renewable energy implementation is influenced by similar socio-political factors in addition to technological feasibility.

2. Review of literature

Renewable energy policy frameworks are constantly evolving. Factors that affect policies include the increasing demand for energy, the requirement by government to reduce carbon footprint, the drive to provide affordable electricity to all citizens and government legislation. It is important to understand the full impact of renewable energy. This includes the benefits associated with its implementation and any negative impacts (Troldborg et al., 2014). There are many significant factors to consider when evaluating the sustainability of energy generation technologies. This includes environmental, social and economic aspects (Evans et al., 2009). The World Bank financed power projects have a customary sustained benefit of approximately 68% bank-wide, compared to projects in the sub-Saharan African region which have an estimated sustained benefit of 36% (Dunmade, 2002). Developed countries concentrate on the management, control and application of various technologies, as well as negating the detrimental effects of past technologies, whereas, developing countries concentrate on rapidly improving the economy and society (Barry et al., 2011). It is therefore imperative to address trade-offs to develop a selection process where the most suitable technology is chosen for a specific location (Troldborg et al., 2014).

2.1. Discussion of factors used to evaluate RETs

Promoting the use of renewables in energy portfolios requires assistance from public and private role players, however, investors are more likely to finance mature technologies (Masini and Menichetti, 2013). Many RETs are still considered emerging technologies in developing countries and therefore perceived to have a certain degree of uncertainty associated with it. Government support in renewables (including political frameworks, subsidies and reduced taxes) is essential for successful implementation (Barry et al., 2011; Cherni and Hill, 2009; Menanteau et al., 2003; Nemet and Kammen, 2007; Jaber et al., 2015; Gabriel, 2016). Both system-level and actor-level (behavioural characteristics of adopters) challenges affect the diffusion of RETs, and the challenges experienced are largely influenced by current institutional frameworks (Mignon and Bergek, 2016). Government support also becomes significant when considering the additional costs associated with RE implementation (Blazejczak et al., 2014; Iddrisu and Bhattacharyya, 2015). Cheung et al. (2016) suggests that climate change mitigation decisions are based on a governing bodies' capacity-to-spend (budget position) and willingness-to-spend (political position). Therefore, economic evaluation alone is not sufficient to understand how investments are made and which RETs are supported.

Transition to a low carbon economy requires financial support from both the public and private sectors (Polzin et al., 2015; Zyadin et al., 2014; Green et al., 2007). Abdmouleh et al. (2015) discusses the financial aspect concerned with the capital investment required for RE projects, which may be greater than current energy projects. RETs that have well established R&D facilities and that have support from government are more likely to receive investments, such as funding for development work. Financial support is an important factor in RE projects and is closely linked to political and technological support systems. However, capital for most conventional power plants was provided by government subsidies and this is not the case for RE plants which are subject to high capital costs (Abdmouleh et al., 2015; Menanteau et al., 2003).

Masini and Menichetti (2012) suggest that investors' decisions are affected by three categories of behavioural factors: a priori beliefs, policy preferences and attitude towards technological risks. It is important to understand the various factors that influence renewable energy investment decisions. 'Gaps' in the information on RETs may slow down the diffusion process. This is related to investors' limited industry knowledge and uncertainty in RETs (Masini and Menichetti, 2013). Table 1 provides a summary of key themes affecting investment in RETs as described in literature.

The predominant common themes emerging across literature with respect to factors affecting investment in RETs include the cost of implementing RETs, the effect of non-financial social and psychological factors, and the lack of systems in place to support implementation of RETs.

A suitable selection process is required for decision-making with regard to RETs. Various factors that inform the selection of RETs were identified in literature. Table 2 summarises the proposed criteria in each study.

There was a difference in the significance placed on various categories used to evaluate RE systems across literature. In some cases, four categories, namely, technical, economic and environmental and social, were deemed relevant. There was further information to support these categories by highlighting the importance of quantifying assessment criteria in order to derive conclusions. However, other authors indicated the importance of assessing socio-political factors when evaluating RETs. These approaches may not be suitable for evaluating technologies in South Africa. The assessment conducted by (Barry et al., 2011) encompassed all factors, technical, economic, environmental, social and political, by focussing on keys aspects that affect implementation of RETs in Africa. This is a holistic approach that is favoured for developing countries.

2.2. Evaluation of criteria for RETs

Following the literature review, technology assessments influence research and development direction, the adoption of new technologies, the technology readiness level, assist in optimum expenditure of capital and aid with market diversification (Musango and Brent, 2011). Development of a framework can assist in performing accurate technology assessments. Stephens et al. (2008) uses the Socio-Political Evaluation of Energy Deployment, (SPEED) framework, which integrates the analysis of laws and regulations, and considers perceptions and beliefs about the risks and benefits of emerging energy technologies. This provides an understanding of the complex interdependent elements of energy systems.

Drawing on the SPEED model, the next challenge lies in assessing various criteria within the technical, economic, environmental, social and political aspects, using suitable analytical methods to draw comparisons, and ultimately determining the relevance of specific criterions. In managing renewable energy sources, the processes that must be considered include production, conversion and transmission, under conditions of uncertainties and complexities (Catalina et al., 2011).

2.2.1. Assessment of criterion

2.2.1.1. Technical. The availability of energy is rated by the type of potential considered. Various types of potentials are used: theoretical, technical, economic and market. Technical factors include capacity factors. The capacity factor is defined as the ratio of actual energy produced to the theoretical maximum capacity (running 24 h a day at the rated power) (Talinli et al., 2010). Theoretical potential represents the highest level of potential, taking into consideration the natural and climatic restrictions. Technical potential is the theoretical potential reduced because of technical limitations such as land-use and topographic constraints. The economic potential is the technical potential but at competitive cost levels. The market potential is the amount of energy that can be implemented, taking into account the demand for energy, competitive technologies, costs and subsidies. Between all the potentials mentioned above, gaps still exist, which means the different renewable energy technologies may not be rated correctly (Grigoras and Scarlatache, 2015). Grigoras and Scarlatache (2015) use a clustering based data mining method to assess the technical exploitable potential (i.e. expected energy production) of renewable energy sources for electricity generation in Romania.

Qualitative assessment of technology maturity, on a scale from 1 to 5, indicates whether a technology has a very high maturity (product is commercialised with a strong market position) or a low level of maturity (product/technology has only been tested at laboratory scale). Reliability can be measured qualitatively, on a scale of 1–5, where number 5 represents energy that is stable and discontinuous. The efficiency of the energy supply can be measured by determining the ratio of actual power output to theoretical maximum output, also termed the availability of the energy i.e. the ratio of the online time to the maximum available time (Troldborg et al., 2014). The variability in the estimates achieved is due to different assumptions used, the method of forecasting potential power generation estimates, and whether the estimates are based solely on the availability of the resource, or if other practical considerations or constraints are factored into the estimates (Troldborg et al., 2014).

2.2.1.2. Economic. Considering the renewable energy policy for a specific renewable energy sector, the levelised cost of electricity (LCOE) can be determined. The LCOE is a constant value and reflects the total cost of construction and operation of a generating plant over its life span. It is the minimum price that the energy can be sold for so that the project breaks even (Lee and Zhong, 2014). LCOE includes all the costs over the systems' lifetime (i.e. capital costs, initial investment, operation and maintenance, and fuel cost). It is also takes into consideration various contributing factors, such as efficiency, production per annum, and service life (Troldborg et al., 2014). The LCOE method is widely used to estimate the cost of lifetime-generated energy for energy technologies (Ouyang and Lin, 2014). LCOE can therefore be used to show the advantage of

Table 1
Key themes affecting investment in RETs as described in literature.

Thematic Factors affecting investment	Reference
Cost implications, such as high capital costs, associated with implementing technology and resources to projects. Generally, large investments are required to move toward a low carbon economy.	(Troldborg et al., 2014), (Masini and Menichetti, 2012), (Abdmouleh et al., 2015), (Menanteau et. Al., 2003)
Non-financial factors that contribute toward the low success rates of RETs in Africa. This includes the lack of skilled resources available locally, acceptance of RETs by disadvantages communities, and investor perceptions.	(Barry et al., 2011), (Masini and Menichetti, 2012)
Less support for RETs related to technology maturity and investor confidence, government influence and lack of policies, legal frameworks and structure in place to drive implementation.	(Barry et al., 2011), (Masini and Menichetti, 2012), (Masini and Menichetti, 2013), (Cherni and Hill, 2009), (Menanteau et al., 2003), (Nemet and Kammen, 2007), (Jaber et al., 2015), (Gabriel, 2016), (Mignon and Bergek, 2016), (Abdmouleh et al., 2015), (Kousksou et al., 2015), (Nguyen, 2007)

Table 2
Significant criteria for assessing RETs as described in literature.

Assessment criteria in literature	References
Criteria used to evaluate the energy supply systems in literature are mainly divided into four categories: technical, economic, environmental and social criteria. The direct benefits of low carbon technologies are related to environmental, economic and societal aspects. Social aspects include social acceptability and job creation.	(Grigoras and Scarlatache, 2015), (Masini and Menichetti, 2012), (Wang et al., 2009)
In contrast, other factors identified that can affect the success of renewable energy technology include financial, fiscal, legislative and political aspects. This can be further assessed as socio-political factors that can be divided into five groups: institutional (political and technological mechanisms in place), regulatory and legal, political, economic and social. When considering regulations, political factors and legalities pertaining to RETs, one needs to consider existing energy policies, decisions, national energy plans and government targets in place. Reaching these targets increases the market share in renewables. RE projects are also generally of a small scale compared to conventional energy plants, with intermittent supply of energy, and therefore grid access legislation is an important factor to consider.	(Abdmouleh et al., 2015), (Stephens et al., 2008), (Kousksou et al., 2015), (Nguyen, 2007)
Eleven important factors identified to assess RETs in Africa were as follows: technology factors, ease of maintenance and support throughout the life cycle of the RET, transfer of knowledge and skills to the relevant people in Africa; site selection factors, identification of a local champion to support the RET after implementation, adoption by the community, identification of suitable sites for pilot studies, site accessibility; economic/financial factors, economic development, availability of finance, ability of the organisation to achieve its goals, project management, financial capacity and technological capacity. New factors that were identified to be important included government support and environmental benefits	Barry et al. (2011)
Quantitative results are important to support the potential advantages and disadvantages of implementation RE. These include potential power generation and reliability of the energy supply, greenhouse gas emissions and other environmental effects, area requirements for implementation, the levelised cost of energy (LCOE), potential income generated, operation and maintenance costs, and the number of jobs created.	(Trianni et al., 2014a), (Troldborg et al., 2014), (Wang et al., 2009)

renewable energy within a country. Learning curves can be used to predict the future costs of products and services based on historical trends which takes into account factors such as increased competition, innovation, learning by doing and economies of scale (Walwyn and Brent, 2015). The costs associated with grid expansion or upgrades, combined with geographical location (which affects transmission investment), are also important to consider in determining the LCOE (e.g. grid in a rural area versus urban area) (Lee and Zhong, 2014).

Economic factors such as capital cost (initial investment costs), operations and maintenance costs, fuel cost and unit price of electricity produced, can be assessed according to the installed total capacity or the unit electricity production (e.g. Rand/kWh) (Talinli et al., 2010).

2.2.1.3. Environmental. Troldborg et al. (2014) uses a Life Cycle Analysis (LCA) approach to assess the environmental impact of a product through all its stages, however, it is only successful if the environmental impacts are quantifiable e.g. CO_2 emissions. LCA has yet to integrate environmental, economic and social factors within a framework. The total GHG emissions from a specific energy system is an indicator used widely for evaluating renewables. It is measured in equivalent emission of CO_2 per energy unit produced (g CO_2 eq./kWh). To measure the emissions throughout the LCA, the following life stages of the energy system are typically considered: fuel and transportation costs, construction, operation and maintenance, and disposal. The impact on amenities refers to other environmental impacts associated with renewables, such as, visual, noise and odours and ecosystem and landscape disturbance (Troldborg et al., 2014). The land area requirements are important to consider since RETs are in competition for land with, for example, agricultural development and conservation. The area requirements are measured quantitatively in m^2/kW of installed power (Troldborg et al., 2014).

2.2.1.4. Social. The financiers' perspective toward risk and return can be summarised as follows. The development finance phase is the most speculative. There is a risk of total loss of the funds invested. Therefore most of the finance comes from the developer or other equity investors. Equity investors will expect a high return. The construction phase represents the capital cost of the RE project. Risk is reduced due to creation of assets, therefore equity and debt financing is expected during this phase. A high return is expected. During the operation financing phase, the project has been transformed into an asset that generates income. There is less risk and debt is available at a lower cost for operation financing (Lee and Zhong, 2014). Other social factors include occupational and public health and public acceptance (Talinli et al., 2010). The contribution to the economy is concerned with evaluation of the social and economic impacts associated with renewable energy endeavours. This includes job creation and new businesses. For many governments, job creation remains a motivating factor for the development and deployment of RETs. It can be measured qualitatively, on a scale from 1 to 5, where achieving high and sustained impact on the local economy is indicated by 5 (Troldborg et al., 2014).

Social acceptability is determined by assessing the public acceptance of the different renewable energy technologies. It is very difficult to measure social acceptance, acceptance varies from location to location and perceptions change over time. It is measured qualitatively from 1 to 5 where 5 indicates strong general support (Troldborg et al., 2014).

2.2.1.5. Political. It is important to use global benchmarks when assessing various renewable energy technologies, as discussed by Walwyn and Brent (2015). Jaber et al. (2015) determine the existing electricity generation mix by developing a database of total electricity supplied from 2006 to 2012 by the generation companies, IPPs, and various industrial self-generators (as well as imports). Lee and Zhong (2014) suggests two analytical approaches for predicting return on renewable energy projects, the top down and bottom up approaches. A top down forecasting approach uses macroeconomic data whereas bottom up forecasting begins with microeconomic information. After classification, indicators such as GDP, inflation, unemployment rate and electricity growth can be analysed. Policy designs can be analysed, this includes, regulatory policies, fiscal incentives and public financing. Analyses of the policies reveal the current and future renewable energy positions and any room for investment. Compounded annual growth rate (CAGR) is one of the tools that can be used to estimate the expected growth rate of renewable energy to fulfil the required goals (Lee and Zhong, 2014). Measuring political support is complex. Stephens et al. (2008) suggest three research approaches that will assist with improving the understanding of socio-political factors. These are policy review and analysis, media analysis, and focus groups and structured interviews with key stakeholders.

2.2.2. Data collection methods

In the study by Barry et al. (2011) information was gathered from sources of evidence: documents, interviews and direct observations. Each database was analysed in a pattern manner (Barry et al., 2011). Focus groups and structured interviews are useful for the understanding of strategic, tactical, and operational factors, required to assess the perceptions of risks and benefits of emerging energy technologies among various stakeholders. General public surveys provide the general public opinion, but the information is limited with regard to perception because the public is predominantly unaware and/or uninformed about emerging energy technologies. This calls for the coordination of focus groups with opinion leaders, decision-makers, and energy-technology-gatekeepers (individuals with strong influence in RET decision-making). Focus groups and structured interviews are more relevant to obtaining data of the social implications (i.e. perceptions, community experiences, emotions etc.) on diffusion and adoption of emerging technologies (Stephens et al., 2008). Knowledge discovery is the process of extraction of information from a database. The data may be implicitly present in the data, previously unknown and of potential significance. This is referred to knowledge discovery in databases (KDD). KDD involves a number of steps: Data selection; Pre-processing; Data transformation; Data mining; Result interpretation/validation; Incorporation of the discovered knowledge (Grigoras and Scarlatache, 2015).

The following research adopted a mixed data collection approach as discussed in section 3, where quantitative data was obtained from semi-structured interviews and qualitative data obtained from literature and other sources.

2.2.3. Multi-criteria analyses

Post 1980s, growing environmental awareness and social considerations resulted in the need to address these factors using multi-criteria approaches. Multi-criteria analyses can reduce uncertainties by quantifying the factors for comparison of various RETs. Increased competitiveness from conventional fuels presents a need to identify barriers to RET penetration and diffusion, and attempt to rectify them (Pohekar and Ramachandran, 2004).

2.2.3.1. Relevance of multi-criteria analyses to energy technology evaluation. Multi-criteria decision making (MCDM) methods refer to the process of making decisions where there exists multiple objectives. The process usually consists of objectives that are conflicting, which may require multiple groups of decision makers. All criteria and opinions must be resolved within a framework of understanding and mutual compromise (Mattiussi et al., 2014). Methods of analyses include priority based, outranking, distance based and mixed methods, for application to various problems. Each method has its own characteristics and the methods can also be classified as deterministic, stochastic and fuzzy methods. The use of a weighted sum method is most commonly used in single dimensional problems (Pohekar and Ramachandran, 2004). MCDM methods are suitable to use in the selection of energy sources (Streimikiene et al., 2012). MCDM methods are generally used for evaluating and comparing the sustainability of different RETs. However, due to the uncertainty in the input data, the results achieved from MCDM methods are generally associated with uncertainty and variability.

Also, different studies arrive at different criteria values, and there is an inconsistent use of units, which contribute to the uncertainty. An example of this is job creation, where reported numbers can vary by orders of magnitude between studies. For assessments at local levels and for site-specific energy projects, the degree of uncertainty may be significantly smaller. However, due to the complex interactions of the energy system and difficult decisions, MCDM methods are the proposed method of analysis. Characteristics of complex systems include conflicting objectives, varying forms of data and information, different perspectives, and evolving physical and socio-economic systems. This can be used as a method to solve complex energy management problems (Wang et al., 2009).

MCDM methods have been widely applied for assessing and comparing the sustainability of different RETs, plans and policies, both in specific areas or regions, or for more generic assessments. Different alternatives are assessed on selected criteria, weightings are assigned to the criteria and a method is used to rank the alternatives based on how well they performed against the criteria. The criteria are carefully selected based on the availability of quantitative and qualitative data for those specific criteria (Troldborg et al., 2014). There are a few disadvantages to using multi-criteria analyses. Firstly, due the complexity of the energy sector, it is difficult to select suitable criteria for analysis. Secondly, obtaining objective weightings for each criterion is difficult, as weightings are generally allocated by experts in the field, therefore elements of subjective influence on the results cannot be excluded.

With the many energy alternatives and potential energy solutions available, it is important to employ a decision support method (Catalina et al., 2011). MCDM methods are an approach that is capable of handling large amounts of variables and assessing alternatives and assists in mapping out the problem to the user. MCDM methods can be classified into two groups, compensatory and outranking. Compensatory method adoption is more applicable to assessment of RETs, where the strengths and weaknesses of the various technologies can be highlighted and trade-offs made.

2.2.3.2. Application of weighted methods. With the many energy alternatives and potential energy solutions available, it is important to employ a decision support method (Catalina et al., 2011). Multi-criteria decision methods are an approach that is capable of handling large amounts of variables and assessing alternatives and assists in mapping out the problem to the user. The analytical hierarchy process (AHP) decomposes the problem into a hierarchy with the goal objective at the top. Elements at each hierarchy level are compared in pairs to assess their relative weighting with respect to each of the elements at the next higher level. The entries of final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. The disadvantage lies in assigning the relative weighting for each element of the hierarchy (Pohekar and Ramachandran, 2004). Table 3 provides a summary of the different approaches used to evaluate technologies using modified AHP methods, as described in literature.

Table 3
A summary of the various analytical approaches used in literature to evaluate RETs.

Analytical approaches in literature	References
The standard preference scale used for AHP is 1–9 scale, which lies between "equal importance" and "extreme importance". Different evaluation scales, such as 1–5 can be used. In the pair wise comparison matrix, the value of 9 indicates that one factor is more important than the other; the value of 1/9 indicates that one factor is less important than the other, and the value of 1 indicates equal importance	Talinli et al. (2010)
A triangle fuzzy number scale is required to make a series of pair wise comparison among the main factors and sub factors using Chang Fuzzy AHP model (Chang, 1996). Chang's extent analysis depends on the degree of possibility of each criterion. It uses expert opinions to determine triangular fuzzy values for linguistic terms, and thus a pair wise comparison matrix is constructed for each level on a hierarchy. To reach comparison of energy types on top of the AHP the following steps are followed: (a) A series of pair wise comparisons are made, (b) synthetic numbers are calculated using the Chang equation, (c) the synthetic numbers are compared and minimum ones chosen, (d) the synthetic results are normalised and priority numbers found, (e) these priority numbers (relative weights) are aggregated and synthesized for the final measurement of the main goal, which is comparison of Energy Production Processes (EPPs) based on the scenario. Comparison of the main factors are analysed and factors for individual EPPs are assessed.	(Talinli et al., 2010), (Chang, 1996)
The Additive Ratio Assessment (ARAS) method, describes a utility function value determining the complex relative efficiency of a feasible alternative which is directly proportional to the relative effect of values and weights of the main criteria considered in a project. The first stage is decision-making matrix (DMM) forming. In the MCDM approach any problem to be solved is represented by DMM of preferences for (m) feasible alternatives (rows) rated on (n) significant full criteria (columns).	Štreimikienė et al. (2016)

The AHP approach is applicable for the evaluation of RETs and other energy producing technologies. Luthra et al. (2015) used the standard AHP method as a decision tool to rank identified barriers to renewable energy technology adoption in India. Talinli et al. (2010) used MCA to identify priority numbers that could be used for decision for the selection of Energy Production Processes (EPPs), following the approach of Chang (1996).

Štreimikienė et al. (2016) used two multiple criteria methods, namely AHP and ARAS (Additive Ratio Assessment), in the assessment of sustainability and the development of the energy sector. A ratio scale and the use of verbal comparisons were used for weighting of quantifiable and non-quantifiable elements. This method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The assessment of the 6 main available electricity generation technologies in Lithuania was performed by applying the set of economic, environmental, social, institutional-political and technological criteria based on experts' surveys (Štreimikienė et al., 2016). The research approach was broken down into phases, the weights of importance of the criteria groups (e.g. technological, political, economic etc.) were determined during the first stage.

The AHP method is widely analysed, including a considerable number and variety of articles written by different authors on application of this method, its advantages and disadvantages (Ahmad and Tahar, 2014; Aragonés-Beltrán et al., 2014).

3. Methodology

Following the literature review, factors considered for the assessment of utility scale technologies include technical, economic, environmental, social and political. Criteria within each factor were selected from literature based on the degree of relevance to the energy sector in South Africa. The ease at which the information can be obtained was also considered as this directly affects the validity of the results.

3.1. Framework for analysis of RETs in South Africa

The framework presented in Fig. 1 captures the relevant criteria for the purpose of analyses of RETs in the South Africa. The main goal, comparison of RETs, exists at the top of the framework hierarchy. A total of 15 criteria were assessed during 2016 for the purpose of this study. The factors or categories, technical, economic, environmental, social and political, provide the context for evaluation of the technologies. Within each category there are criteria which will be evaluated for each RET namely, solar PV, wind, CSP, hydro, biogas and biomass energies.

All criteria are evaluated within the existing regulatory structure for RETs, and conform to the existing national energy plans and existing government targets, such as the integrated resources plan (IRP).

3.2. Overall research approach for the assessment

Each of the 15 criteria were evaluated either quantitatively or qualitatively, and the data gathered was used to determine the end objective, namely, comparison of RETs in South Africa. The overall research approach for achieving the objective is presented in Fig. 2.

3.2.1. Qualitative and quantitative data gathering

In accordance with part (a) and (b) of Fig. 2, semi-structured interviews were conducted with 9 experts in the renewable energy sector. The role of each interviewee is indicated in Table 4. The questionnaire was developed with the purpose of obtaining the necessary information to populate the framework of 15 criteria indicated in Fig. 1. The interviews were conducted according to the research approach and keeping in line with the pre-defined matrix (table A in the Appendix), for the following technologies: solar PV, wind, CSP, hydro, biomass and biogas. The data from the interviews was analysed using *Atlas.ti* qualitative data analysis software package (Atlas.ti, 2016). *Atlas.ti* enables extraction and interpretation of thematic information from qualitative data and has been used to identify barriers in the energy sector (Ahlborg and Hammar, 2014), assess innovation in the power sector (Rogge et al., 2011) and also to analyse governance and legislation in the nuclear industry (Heffron, 2013; Ruuska et al., 2011).

The data (i.e. responses to the specific questions regarding the technical, economic, environmental, social and political aspects of RETs) was coded according to the similarities (or themes) found in the responses (i.e. dialogue, quotes and phrases), and rated using the pre-defined matrix in table A. By the nature of the analyses, this was an interpretive process therefore the codes were kept consistent throughout the analyses to prevent a biased approach or misinterpretation of the data. A list of codes was generated and the frequency of a particular code was determined.

In accordance with part (d) of Fig. 2, other data was gathered

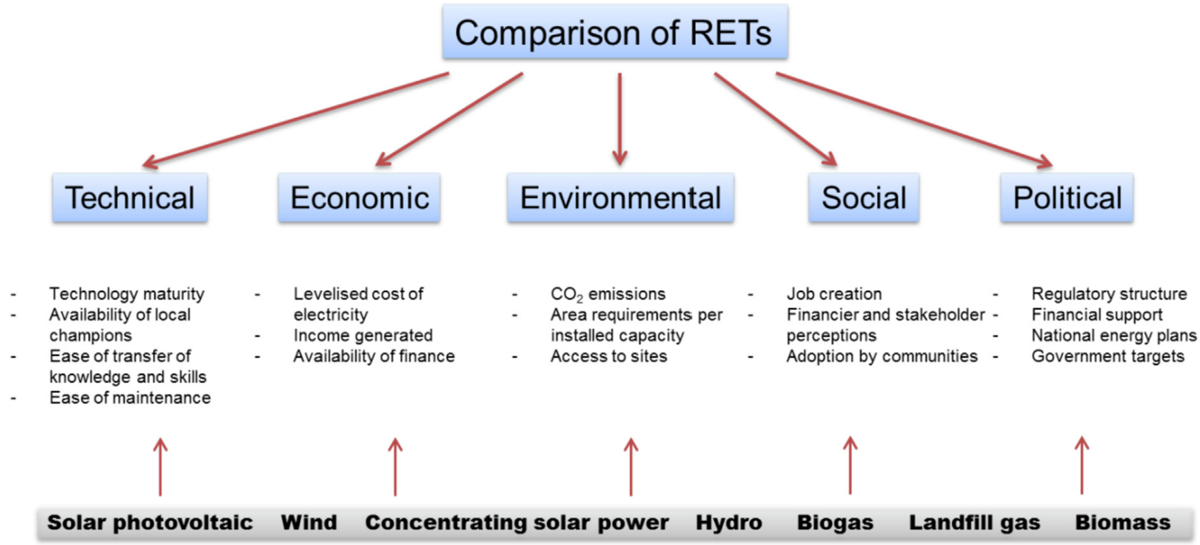

Fig. 1. Framework for evaluation of renewable energy technologies in South Africa.

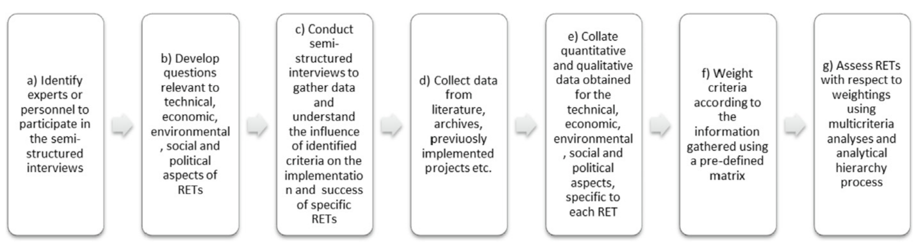

Fig. 2. Overall research approach for assessing renewable energy technologies in South Africa.

Table 4
Role of each interviewee within the RE sector.

no.	Interviewee position	Role in RE sector
1	Academic	Economist. Focus on economic and political aspects within the RE sector
2	Academic	Focus on engineering management and sustainable development within the RE sector
3	Individual employed by IPP	Project management and implementation within RE sector
4	Individual employed by IPP	Project management and implementation within RE sector
5	Individual employed by IPP	Project management and implementation within RE sector
6	Individual employed by IPP	Project management and implementation within RE sector
7	Employee in a government institution	Responsible for approval of funding and project management of RE-funded projects
8	Employee in a government institution	Expert in RE initiatives within the energy center
9	Senior Engineer	Implemented RE projects on site

from literature, historical archives and existing policies. The following research approach used both quantitative and qualitative methods to measure criteria for specific RETs. Quantitatively assessed criteria, such as LCOE was obtained from literature (Appendix A). Qualitative information, such as social impact and job creation was obtained from historical information and interviews with key experts. The responses from the interviewees was substantiated with data from literature, project close out reviews or the IRP update (Department of Energy, 2013).

3.2.2. *Matrix used to determine weightings*

Each criterion was assessed for each technology, either quantitatively or qualitatively, for input into the framework. This process determines the validity of the criteria input into the framework. It also ascertains whether there is sufficient knowledge and data associated with a specific criterion, such that an objective opinion can be formed and relative weighting allocated. Weightings are determined for the data gathered, for each renewable energy technology (part (f) of Fig. 2), using the pre-defined matrix in table A of the Appendix. The weightings are required for the DMM discussed in section 3.2.3. Mixed data collection methods were used as discussed in section 3.2.1. Drawing from other studies accroding to Table 5, the scale for weighting the qualitative data, related to responses from semi-structured interviews conducted, was kept consistent (scale of 1–4) and termed the performance value. The frequency of each code (section 3.2.1) and the performance value for each criterion was determined. In each case, 4 represented the best/favoured result. In parallel, the quantitative data gathered was also evaluated using the matrix developed.

Ultimately, it is important to provide sufficient information for each criterion in order to weight criteria effectively and apply the AHP method (section 3.2.3).

Table 5
Representation of decision making matrix (DMM) of performance values.

Criteria	Units	*Technologies*						*Reference*
		Solar PV	Wind	CSP	Hydro	Biomass	Biogas	
Technical								(DOE South Africa, 2011a), (Troldborg et al., 2014)
1. Technology maturity	1 - 4 (min - max)	4 (4–4)	4 (4–4)	3.13 (3–4)	3.67 (3–4)	2.8 (2–4)	2.83 (2–4)	
2. Availability of local champions	1 - 4 (min - max)	4 (4–4)	4 (4–4)	2 (2–2)	2 (2–2)	2 (2–2)	2 (2–2)	
3. Ease of transfer of knowledge and skills	1 - 4 (min - max)	4 (4–4)	3.5 (2–4)	2.4 (1–4)	3.25 (3–4)	3 (2–4)	2.5 (2–4)	
4. Ease of maintenance	1 - 4 (min - max)	3.38 (2–4)	3.2 (2–4)	2.8 (2–3)	3.5 (3–4)	3.33 (3–4)	3.25 (3–4)	
Economic								
5. Levelised cost of electricity	R/MWh	1621.1	693.9	1488.1	247.4	2822.3	1736.8	Montmasson-Clair and Ryan (2014)
6.a. Income generated	1 - 4 (min - max)	3.22 (3–4)	3.17 (2–4)	3 (2–4)	1.86 (1–2)	2.13 (1–3)	2.13 (1–3)	
6.b. Income generated by the product of the technology	R/kWh	0.88	0.66	1.46	1.03	1.24	0.84	
Environmental								
7.a. CO2 emissions and waste	1 - 4 (min - max)	3.67 (3–4)	3.75 (3–4)	2.67 (2–3)	4 (4–4)	2 (2–2)	2 (2–2)	
7.b. Impact on land, plant and animal life	1 - 4 (min - max)	3.5 (3–4)	3.3 (3–4)	3 (2–4)	1.5 (1–2)	2 (1–3)	2.33 (2–3)	
7.c. Greenhouse gas emissions from literature	g CO^2 eq./kWh	60	15	40	20	100	350	Troldborg et al. (2014)
8. Area requirements per installed capacity	m^2/kW	150	200	40	500	4000	25	Troldborg et al. (2014)
9. Access to sites	1 - 4 (min - max)	3.43 (3–4)	3.43 (3–4)	2.86 (2–4)	2 (2–2)	2.8 (2–4)	3.33 (3–4)	
Social								
10.a. Job creation	1 - 4 (min - max)	2.33 (2–3)	2.33 (2–3)	3 (2–4)	3 (3–3)	3.33 (2–4)	2.5 (2–3)	
10.b. Job creation from literature	jobs/MW	21.4	14.1	24.1	–	–	–	Montmasson-Clair and Ryan (2014)
11. Financier and stakeholder perceptions	1 - 4 (min - max)	4 (4–4)	3.67 (3–4)	2.67 (2–4)	2 (2–2)	2 (2–2)	2 (2–2)	
12. Adoption by communities	1 - 4 (min - max)	2.67 (2–4)	3 (2–4)	3.67 (3–4)	3 (2–4)	3.67 (3–4)	3 (2–4)	
Political								
13. Financial support	%share	32	38	28	1	1	0	DOE South Africa (2015)
14. National energy plans	MW	1484	1984	400	14.3	16.5	18	Rycroft (2013)
15. Government targets	1 - 4 (min - max)	3.67 (3–4)	3.5 (3–4)	3.14 (2–4)	1.83 (1–3)	2.2 (2–3)	2 (2–2)	

3.2.3. Analytical hierarchy process (AHP) method

The Analytical Hierarchy Process (AHP) was selected to perform the analyses on existing and potential RETs in South Africa (part (g) of Fig. 2). The AHP pair-wise comparison method is suitable for determining relative weights of importance of criteria, obtained either quantitatively or qualitatively. The weightings are then used to compare technologies against the criteria using a decision making matrix. The AHP and Additive ratio assessment (ARAS) as discussed by Štreimikienė et al. (2016) was adapted for evaluation of the technologies or alternatives (section 2.2.3.2).

The methodology was adapted as follows:

1) Develop a decision-making matrix (DMM) that represents the problem. The DMM consists of preferences for n feasible alternatives (columns) rated on m significant criteria (rows) and is represented below:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & & \vdots & & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & & \vdots & & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix}; i = \overline{1,m}; j = \overline{1,n} \tag{1}$$

Where n is the number of alternatives (in this case RETs), m is the number of criteria describing each alternative, x_{ij} represents the performance value of the jth alternative in terms of the ith criterion, and x_{iO} is the optimal value of the ith criterion. If the optimal value is maximised then x_{iO}=max x_{ij}, whereas if the optimal value is minimised then x_{iO} = min x_{ij}. The performance values x_{ij}, calculated using the quantitative and qualitative data, are entries into the DMM.

2) The criteria measured will have different dimensions, for example the units for technology maturity are dimensionless whereas the units for CO_2 emissions are CO_2 eq./kWh. To prevent difficulty, the ratio of the optimal value is used. The values are then normalised on the interval [0; 1] to form the normalised DMM represented below:

$$\overline{X} = \begin{bmatrix} \overline{x}_{11} & \cdots & \overline{x}_{1j} & \cdots & \overline{x}_{1n} \\ \vdots & & \vdots & & \vdots \\ \overline{x}_{i1} & \cdots & \overline{x}_{ij} & \cdots & \overline{x}_{in} \\ \vdots & & \vdots & & \vdots \\ \overline{x}_{m1} & \cdots & \overline{x}_{mj} & \cdots & \overline{x}_{mn} \end{bmatrix}; i = \overline{1,m}; j = \overline{1,n} \tag{2}$$

If the preferable values are maxima, the normalisation procedure is as follows:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{3}$$

If the preferable values are minima, the two-stage normalisation procedure is as follows:

$$\overline{x}_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}} \text{ where } y_{ij} = \frac{x_{ij}(\min)}{x_{ij}} \tag{4}$$

3) Values of the scoring function S_J are determined as follows:

$$S_j = \sum_{i=1}^{m} \overline{x}_{ij}; j = \overline{1, n} \quad (5)$$

Where, S_j is the value of the scoring function of the jth alternative for each factor. The greater the value of the scoring function the more effective the technology.

4. Results and discussion

A total of 15 criteria were assessed for the purpose of this study. The values in Table 5 derived using equation (1) represent the decision making matrix of performance values, for each technology. The average values, minimum and maximum ranges for the specific qualitative data are presented.

In order to relate the qualitative and quantitative data and, to compare results between technologies, the data was normalised according to equations (2)–(4), and the scoring function calculated according to equation (5). The normalisation was performed according to the procedure below:

a. The normalisation is performed in accordance with section 3.2.3 (equations (2)–(4)).
b. For example, the preferable values for technology maturity is a maxima, therefore equation (3) is utilised. The optimise functions for the other criteria (i.e. minima or maxima) is shown in table A.
c. Input performance values for technology maturity across the various technologies.
d. Utilisation of equations (2)–(4) for normalisation yields:

$$\overline{x}_{techno\ \log y\ \ maturity,CSP} = \frac{3.13}{4+4+3.13+3.67+2.8+2.83} = 0.15$$

e. Similarly, other normalised values were calculated.
f. Using equation (5), a score is determined for each factor, technical, economic, environmental, social, political, with respect to each technology.

Table 6 presents relative weightings of each criterion across all technologies. The scoring function values are also presented, for comparative weighting of each factor across all technologies.

4.1. Summary of findings from evaluation of RETs

The following evaluation of RETs is provided with reference to the performance values (Table 6) for each factor. With respect to the technical factor, the scoring value was the highest for solar PV (0.83) followed by wind (0.80), whilst the scoring value was the lowest for CSP technology (0.55). The highest scoring is due to the availability of local champions and the ease of transfer of knowledge and skills for the implementation of solar PV technology. During the study, most of the interviewees believed that all technologies are at commercial scale, however it was suggested that CSP is currently not as mature as solar PV and wind technologies, hence the lower scoring. CSP RE however, has the potential for storage and will therefore become relevant in the future. Solar PV and wind technologies can improve on technical capabilities in maintenance; however the common sentiment was that South Africa is well-equipped (technically) to tackle solar PV and wind technologies.

Within the economic factor component, the scoring value was the highest for hydro (0.81) followed by CSP (0.52), whilst the scoring value was the lowest for biogas technology (0.35). The highest scoring is due to the lowest levelised cost of electricity for hydro technology. This is consistent with the study performed by Ahmad and Tahar (2014) where the sourced investment cost was the lowest for implementing hydro technology. The LCOE was expressed as highest to lowest for the purpose of this study. The LCOE for hydro technology was 247.42 R/MWh versus the highest LCOE of 2822.30 R/MWh for biomass followed by 1736.80 R/MWh for biogas technology. The second highest scoring value was generated for CSP technology. Fairly consistent financial estimates can be generated for CSP due to the lack of intermittency, especially with regard to meeting future targets. The technology may also be attractive due to the scale it can be implemented at. Price is the largest determinant in the awarding of bids; too high a price means the government is offering too high returns whereas too low returns means the tariffs are set too low. However, a higher tariff means a higher return on investment for developers but also increases the commercial viability of the renewables sector (income generated). Due to the price point, CSP technology achieved the highest performance value (0.24). The potential of the various technologies to generate income in South Africa was obtained qualitatively via interviews. The current REI4P price caps (during Bid Round 2 and 3) were used to confirm the income generated by various technologies. CSP has the higher tariff and corresponds to the respondents' views. The cost of electricity in Africa is kept to a minimum and large profits are not planned for (Barry et al., 2011). IPPs are reliant on the government to subsidise renewable energy technologies; therefore the rollout of the various technology capacities by the REI4P directly influences whether a technology will be implemented or not.

With respect to the environmental factor, the scoring value was the highest for wind (1.06) followed by biogas (0.97), whilst the scoring value was the lowest for biomass technology (0.46). In the study performed by Ahmad and Tahar (2014), wind technology also performed the best on environmental criteria for a case in Malaysia. The scoring for wind and biogas technologies is due to low greenhouse gas emissions (resulting in a high performance value of 0.39) and low area requirements per installed capacity (resulting in a high performance value of 0.51), respectively. The area requirements for biogas technology was 25 m^2/kW versus the highest area requirement of 4000 m^2/kW for biomass technology. Across all the technologies, impact on the environment was presented in different forms (waste, effect on animal life, noise pollution etc.). The frequency of statements made by the respondents allowed for assessment of the commonality or themes across the interviews. The performance value that also resulted in low scoring, particularly for hydro and biomass technologies, was access to a suitable site. Large hydro projects may result in diversion of rivers and displacement of people. With regard to biomass RE there are logistic concerns, such harvest (and sustenance) of crops and distribution of the feed supply to the plant. The respondents did not view biomass RE as an environmentally friendly technology due to the emissions and waste generated.

According to the social factor component, the scoring value was the highest for CSP (0.94) followed by solar PV (0.89), whilst the scoring value was the lowest for biogas technology (0.43). The scoring for CSP and solar PV is due to the greater number of jobs created (from literature) versus the other technologies. Based on the performance values (10.a. Job creation), technologies that have the potential for higher job creation include CSP, hydro and biomass technologies. The job creation from literature versus the favourability of the technology to create jobs therefore correlates well for CSP. Bids (REI4P) are scored on weight criteria; a maximum of 70% is awarded for the price contribution and 30% for economic

Table 6
Representation of normalised DMM of performance values and scoring values for each factor (technical, economic, environmental, social and political) across each technology.

Criteria	*Technologies*					
	Solar PV	Wind	CSP	Hydro	Biomass	Biogas
Technical						
1. Technology maturity	0.20	0.20	0.15	0.18	0.14	0.14
2. Availability of local champions	0.25	0.25	0.13	0.13	0.13	0.13
3. Ease of transfer of knowledge and skills	0.21	0.19	0.13	0.17	0.16	0.13
4. Ease of maintenance	0.17	0.16	0.14	0.18	0.17	0.17
	0.83	0.80	0.55	0.66	0.59	0.56
Economic						
5. Levelised cost of electricity	0.08	0.19	0.09	0.52	0.05	0.07
6.a. Income generated	0.21	0.20	0.19	0.12	0.14	0.14
6.b. Income generated by the product of the technology	0.14	0.11	0.24	0.17	0.20	0.14
	0.43	0.50	0.52	0.81	0.39	0.35
Environmental						
7.a. CO_2 emissions and waste	0.20	0.21	0.15	0.22	0.11	0.11
7.b. Impact on land, plant and animal life	0.22	0.21	0.19	0.10	0.13	0.15
7.c. Greenhouse gas emissions from literature	0.10	0.39	0.15	0.29	0.06	0.02
8. Area requirements per installed capacity	0.08	0.06	0.32	0.03	0.00	0.51
9. Access to sites	0.19	0.19	0.16	0.11	0.16	0.19
	0.80	1.06	0.96	0.75	0.46	0.97
Social						
10.a. Job creation	0.14	0.14	0.18	0.18	0.20	0.15
10.b. Job creation from literature	0.36	0.24	0.40	–	–	–
11. Financier and stakeholder perceptions	0.24	0.22	0.16	0.12	0.12	0.12
12. Adoption by communities	0.14	0.16	0.19	0.16	0.19	0.16
	0.89	0.76	0.94	0.46	0.52	0.43
Political						
13. Financial support	0.32	0.38	0.28	0.01	0.01	0.00
14. National energy plans	0.38	0.51	0.10	0.00	0.00	0.00
15. Government targets	0.22	0.21	0.19	0.11	0.13	0.12
	0.92	1.10	0.57	0.13	0.15	0.13

development contributions. Of the 30%, 25% is dedicated to job creation and 15% to socio-economic development, therefore it is important that IPP's meet the targets in order to compete (Montmasson-Clair and Ryan, 2014). The program is expected to contribute to 109 443 employment opportunities for South African citizens. The actual employment to date is 19 033 jobs (DOE South Africa, 2015).

Within the political factor, the scoring value was the highest for wind (1.10) followed by solar PV (0.92), whilst the scoring value was the lowest for hydro (0.13) and biogas technologies (0.13). The scoring for wind and solar PV is due the financial support offered for these RETs as well as alignment to the national energy plans. The energy allocations for wind and solar PV were 1984 and 1484 MW, respectively. This is compared to the low energy allocations for hydro and biomass of 14.3 and 16.5 MW, respectively. Investors are also willing to invest in solar PV and wind technologies predominantly, which is related to the lower risk associated with these technologies. Hydro is a mature technology as well, however due to the lack of suitable sites, environmental support etc., the technology does not seem to gain support for implementation; the percentage share of investment across all the bid windows was a mere 1% (or R1 billion) (DOE South Africa, 2015). CSP has gained a lot of support due to its scalability but from the results it seems that there is still some uncertainty and risk associated with the technology. An advantage is that CSP is also supported within policy, in favour of hydro, biomass and biogas technologies.

4.2. Barriers to adoption of RETs

Barriers to technology adoption and diffusion were highlighted during this study. A barrier that was common amongst all RETs included skills development. This is seen across the performance values of technical criteria (of Table 6) where low scoring is observed across all technologies, and specifically for CSP, for the ease of transfer of knowledge and skills and the ease of maintenance for the technologies. South Africa is generally reliant on the technology provider (international) for skills development. CSP in particular, shows deficiencies with respect to the availability of local champions and the ease of transfer of knowledge and skills. There is capacity within all technologies to develop skills and knowledge. The lack of access to human capital is consistent with findings from the study conducted by Ahlborg and Hammar (2014). The study was also performed within the context of developing countries, namely Tanzania and Mozambique.

From an economic perspective, the high investment and operational costs (presented as LCOE) are not favourable for biomass, biogas and CSP technologies represented by the normalised performance values of 0.05, 0.07 and 0.09, respectively (DOE South Africa, 2011a; Troldborg et al., 2014). This coupled with the lower energy allocations for biomass and biogas (DOE South Africa, 2015), prevent the implementation of these technologies. Biomass and hydro technologies were favourable with respect to the potential to create jobs, however records of job creation, specifically for the REI4P programme, are limited which is a disadvantage against the technologies (DOE South Africa, 2015).

Access to suitable sites was also identified as a barrier. Whilst technologies such as large hydro and biomass technologies have the potential to contribute toward the energy mix and meet government targets, and hydro in particular is perceived as a mature technology, the specific barriers identified impede the adoption process. Large hydro projects may result in diversion of rivers and displacement of people, and therefore there are a limited number of sites that the specific technology can be implemented. Biomass RE relies strongly on the harvesting and distribution of crops to the facility, therefore constant energy generation cannot be guaranteed especially due to logistic concerns, food-versus-energy crops debate as well as water scarcity issues in the country. This is indicated by performance values of 0.11 and 0.16 for access to suitable sites for hydro and biomass RE, respectively. These values are proportional to the large area required to implement hydro and biomass technologies (Troldborg et al., 2014). Biomass RE is also perceived as a high waste generating technology and therefore scored poorly, indicated by a scoring value of 0.46, compared to the other RETs.

Whilst solar PV and wind RE have gained more political support, these entrenched technologies also face barriers to diffusion. The technologies alone will not be sufficient to meet the baseload requirements and must be supplemented with fossil fuel technologies. Also, existing grid infrastructure may not support expansion of the technologies which limits diffusion.

The research results provide a synopsis of the strengths and weaknesses, in terms of performance values calculated, of the RETs. A holistic view of each technology is provided which has the potential to influence decision-making, adoption, diffusion or expansion efforts for specific technologies. Barriers to technology implementation is explicitly presented, which may assist risk-averse investors in their decision making processes. The framework also provides a user-friendly term of reference for drawing on the similarities and differences amongst the various technologies. Overall, the research contributes toward the growth of the renewables sector.

5. Conclusions

Feasible technology options were highlighted following the outcome of the analyses. One of the conclusions inferred, using this framework, was that investors are willing to support solar PV and wind technologies predominantly, due to higher technology maturity and technological advances, financier perception and lower risk associated with these technologies. Solar PV and wind technologies are also technologically advanced and associated with higher technology maturity. One possible policy intervention would for government in partnership with banks/financiers, to incentivise lower lending rates for technologies that have a higher risk perception.

CSP was favoured economically due to scalability of the technology and less intermittence in comparison to the other technologies; its relevance in the future energy mix was sufficiently highlighted, indicated by the high scoring values obtained across the economic, environmental and social factors. The advantage of hydro RE is that it is a mature technology and associated with a low LCOE; there is also potential to create significant jobs with the implementation of Hydro. Hydro RE had the lowest LCOE in comparison to the other technologies which results in a high weighting in the economic aspect; however if the technology has little support from investors and the government the role of LCOE is diminished. Similarly, biomass technology has the potential for job creation. Biogas is favoured from an environmental impact perspective due to the lower land requirement for implementation of the technology. Biomass and biogas technologies scored poorly for most criteria; however the sectors have the potential to create jobs in future and are well perceived by communities. Overall, solar PV and wind technologies were deemed favourable to meet government targets; however many respondents were concerned about storage capacity limitations and concluded that CSP will be necessary in the future due to storage and scalability of the technology.

Specific barriers to adoption were highlighted across all technologies. For the cases of hydro and biomass technologies, barriers identified were more specific such as access to suitable sites for hydro and logistic concerns for biomass which are coupled with the limited energy allocations due to limited government support. Therefore the scoring for the political factor was affected, for hydro, biomass and biogas technologies which further impedes adoption. The low scoring of the specific criteria therefore results in poor financier perception as indicated by the low performance values for hydro, biomass and biogas technologies. Possible policy interventions to promote technologies such as biomass which has higher job creation potential, would be to discourage low cost land filling as well as create incentives and supply chains for waste recycling (Amsterdam and Thopil, 2017).

An important outcome of the research was that there may be limited knowledge transfer for all RETs and shortage of skills in the field of maintenance for all RETs. South Africa is generally reliant on the technology provider (international) for skills development; there is capacity within all technologies to develop skills and knowledge; however with the focus and support directed toward CSP it is imperative that we start building skills within this RE. The need for skills in RE may also be related to the current higher education system, which has recently started catering for learning in renewables. As a policy proposal, higher emphasis will have to be placed on educational and training programmes related to artisan based skills that can cater for support and maintenance of RE projects, thereby compensating for reduction in jobs post construction phase.

6. Recommendations

The framework is applicable for use by government officials, NGOs, academics and IPPs, and can be utilised in various decision making process. It provides the incumbent with information around the performance of various implemented technologies in SA with regard to Technical, Economic, Environmental, Social and Political aspects. The analyses performed using the framework is favoured over conventional techno-economic assessments because it improves the overall understanding of RET selection and implementation in South Africa. The research performed may also influence the adoption and diffusion of various technologies by providing a synopsis of the strengths and weaknesses, in terms of performance values calculated, of the RETs. The framework also provides a user-friendly term of reference for drawing on the similarities and differences amongst the various technologies. It can be used to determine which RETs face barriers to implementation and adoption, which may assist risk-averse investors in their decision making processes. Overall, the research contributes toward the growth of the renewables sector.

Future research can be improved in number of ways. Throughout the research, it was evident that information was easily sourced for solar PV, wind and CSP technologies and not as readily available for biogas, biomass and hydro technologies. It is clear from the analyses that political support for solar PV, wind and CSP RETs may also influence the ease at which data is available. It is recommended to conduct further studies in the field of biogas, biomass and hydro technologies to evaluate the suitability of these technologies in the energy mix. It is necessary that pertinent issues that hinder adoption of the technologies are discussed and evaluated. This includes constant and consistent feedstock supply for the generation of energy.

The research conducted provides a foundation for further studies. Climate change may influence energy forecasts and this may create another area for research in the near future. The future of RE in terms of return to investors must be assessed more extensively, especially with the decrease in tariffs, which renders large scale offerings more profitable. The effect or outcome of the Environmental Impact Assessment (EIA) on the decision whether to implement a technology or not can also be investigated further. Ranking of the technologies was outside the scope of this research but may be useful to pursue in future studies, provided extensive data is available for all technologies assessed. Ranking of technologies would entail a two-step approach. First, obtaining weightings of importance of the technical, environmental, economic, social and political factors with regard to RET implementation in South Africa. Second, weighting of the criteria for each factor. RE implementation in South Africa is currently still developing compared to other implementations globally, therefore given the information available, it would be premature to rank the various technologies.

Ultimately, a combination of technologies that can provide the baseload power requirements will increase competitiveness; reduce tariffs and allow citizens to move away from conventional fossil-derived energy.

Appendix A

Table A
Pre defined matrix used to determine weightings for the decision making matrix

Criteria	Units	Optimise function	Weighting criteria				Data acquisition	References
Technical								
Technology maturity	1–4	Maximise	**High maturity - 4**	**3**	**2**	**Low maturity - 1**	Interviews	Wang et al. (2009)
Availability of local champions	1–4	Maximise	**Available - 4**	**3**	**2**	**Not available - 1**	Interviews	Barry et al. (2011)
Ease of transfer of knowledge and skills	1–4	Maximise	**Little or no challenge - 4**	**3**	**2**	**Many challenges experienced - 1**	Interviews	Barry et al. (2011)
Ease of maintenance	1–4	Maximise	**Support functions available locally - 4**	**3**	**2**	**Support functions not available locally - 1**	Interviews	Barry et al. (2011)
Economic								
Levelised cost of electricity	R/MWh	Minimise	**Lowest LCOE to Higest LCOE**				Literature	(Abdmouleh et al., 2015), (Talinli et al., 2010)
Income generated	1–4	Maximise	**Potential to generate overall income is high - 4**	**3**	**2**	**1 - Potential to generate overall income is poor**	Interviews	Barry et al. (2011)
Income generated by the product of the technology	R/kWh	Maximise	**Highest electricity tariff to lowest electricity tariff**					Barry et al. (2011)
Environmental								
CO2 emissions and waste	1–4	Maximise	**Environmentally friendly (green) - 4**	**3**	**2**	**Harmful to the environment - 1**	Interviews	Wang et al. (2009)
Impact on land, plant and animal life	1–4	Maximise	**Little or no impact - 4**	**3**	**2**	**Harmful to the environment - 1**	Interviews	Wang et al. (2009)
Greenhouse gas emissions from literature	g CO2 eq./kWh	Minimise	**Lowest carbon footprint to most carbon footprint**				Literature	Troldborg et al. (2014)
Area requirements per installed capacity	m^2/kW	Minimise	**Least area required to most area required per energy unit**				Literature	Troldborg et al. (2014)
Access to sites	1–4	Maximise	**Site access granted easily - 4**	**3**	**2**	**Site access is difficult to obtain - 1**	Interviews	Wang et al. (2009)
Social								
Job creation	1–4	Maximise	**High and sustained impact on the local economy - 4**	**3**	**2**	**Little or negative impact on local economy - 1**	Interviews	(Barry et al., 2011), (Troldborg et al., 2014)
Job creation from literature	jobs/MW	Maximise	**Highest jobs created to lowest jobs created per energy unit**				Literature	(Barry et al., 2011), (Troldborg et al., 2014)

Table A (*continued*)

Criteria	Units	Optimise function	Weighting criteria				Data acquisition	References
Financier and stakeholder perceptions	1–4	Maximise	**High propensity to invest - 4**	**3**	**2**	**Risk adverse, low propensity to invest - 1**	Interviews	Masini and Menichetti (2012)
Adoption by communities	1–4	Maximise	**High social acceptability - 4**	**3**	**2**	**Low social acceptability - 1**	Interviews	(Barry et al., 2011), (Troldborg et al., 2014), (Wang et al., 2009)
Political								
Financial support	%	Maximise	**Highest share of investment to lowest share of investment**				Budget information, national energy plans	(Barry et al., 2011), (Department of Energy, 2013), (DOE South Africa, 2011b)
National energy plans	MW	Maximise	**Highest energy allocation to lowest energy allocation**				Allocated capacity information	(Department of Energy, 2013), (DME South Africa, 2002), (DOE South Africa, 2011b)
Government targets	1–4	Maximise	**High potential to meet targets - 4**	**3**	**2**	**Low potential to meet government targets - 1**	Interviews	(Department of Energy, 2013), (DME South Africa, 2002), (DOE South Africa, 2011b)

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