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Renewable energy choices and their water requirements in South Africa

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Abstract
South Africa is an arid country, where water supply is often obtained from a distant source. There is increasing pressure on the limited water resources due to economic and population growth, with a concomitant increase in the energy requirement for water production. This problem will be exacerbated by the onset of climate change. Recently, there have been concerns about negative impacts arising from the exploitation of energy resources. In particular, the burning of fossil fuels is significantly contributing to climate change through the emission of carbon dioxide, a major greenhouse gas. In addition, fossil fuels are being depleted, and contributing to decreased energy security. As a result of this, the international community has initiated various interventions, including the transformation of policy and regulatory instruments, to promote sustainable energy. With this in mind, South Africa is making policy and regulatory shifts in line with international developments. Renewable energy is being promoted as one way of achieving sustainable energy provision in the country. However, some issues require scrutiny in order to understand the water footprint of renewable energy production. Due to the large gap that exists between water supply and demand, trade-offs in water allocation amongst different users are critical. In this vein, the main objective of this study was to investigate and review renewable energy choices and water requirements in South Africa. Data were acquired through a combination of a desktop study and expert interviews. Water withdrawal and consumption levels at a given stage of energy production were investigated. Most of the data was collected from secondary sources. Results show that there is limited data on all aspects of water usage in the production chain of energy, accounting in part for the significant variations in the values of water intensity that are reported in the literature. It is vital to take into account all aspects of the energy life cycle to enable isolation of stages where significant amounts of water are used. It is found that conventional fuels (nuclear and fossil fuels) withdraw significant quantities of water over the life-cycle of energy production, especially for thermoelectric power plants operated with a wet-cooling system. The quality of water is also adversely affected in some stages of energy production from these fuels. On the other hand, solar photovoltaic and wind energy exhibit the lowest demand for water, and could perhaps be considered the most viable renewable options in terms of water withdrawal and consumption.

Keywords: climate change, water-energy nexus, renewable energy, water requirements, South Africa

1. Introduction

1.1 Background

Water use and energy supply are inextricably linked. The provision of energy requires water, and energy is often needed to pump, treat or transport water. The need to protect water quality and supply, and the need to ensure a stable and growing energy supply is an internationally-shared experience. These demands may create competing interests.

The mutually dependent nature of the relationship between energy and water is often referred to as the water-energy nexus. This paper focuses on water requirements for energy production (as opposed to energy for water). It will therefore consider water usage associated with various forms of energy.

The production of electricity may consume a significant quantity of water, be it in the processing of raw materials or in the generation of electricity. In light of the fact that South Africa is a water scarce country, consideration of water use by various energy technologies is important for both future planning and for policy. Climate change is expected to put added strain on water provision, since there are projected changes to seasonal and regional temperature and patterns of precipitation (Hoekstra *et al.,*. 2011; Wilson *et al.,* 2012).

South Africa has a recent history of energy shortages, electricity blackouts in 2007 and 2008, petroleum shortages in 2008 and 2011 and gas shortages in 2011 and 2012. The country is also committed to providing energy for all. However, increasing the output of energy using current production methods will increase the energy demand for water and may involve opportunity cost to the detriment of other developmental activities, or it may increase the vulnerability of communities or watersheds to future threats like changes in the rates of precipitation and evaporation associated with climate change.

South Africa has long protected the integrity of its water sources, and its National Water Act (Act 36 of 1998) is considered to be highly progressive (Seward, 2010). As part of South Africa's water management strategy, the country is divided into 19 water management areas (which have been amalgamated into 9). Each local authority is enabled to regulate the abstraction and use of water within its boundaries. Large-scale water abstraction and use, for example, by mining and some industry is regulated and licenced by the national government. Water resource management in South Africa faces various challenges, which may be compounded by its vulnerability to climate change and related stress on water resources.

To meet the foreseen electricity needs of South Africa in the context of a changing climate, the Department of Energy developed an Integrated Resource Plan (IRP) (DoE, 2010). The national strategy of the Plan is to meet growing electricity demand and at the same time to meet South Africa's international commitment to reduce greenhouse gas emissions by 34% below business as usual by 2030. The IRP strategy is to diversify our energy supply from South Africa's current primary reliance on coal-fired electricity, to an energy mix in which a third is generated by renewable sources (DoE, 2010). To meet this goal, the government is currently offering the opportunity for investment in renewable energy technologies through the Renewable Energy Independent Power Procurement Programme (REIPPP).

The South African Constitution endows each household with the right to 6 000 litres of free water and 50 kWh of electricity per month. In light of the planned changes to the energy supply technologies, and with the risk of increased water vulnerability due to climate change, it is important that the country's water and energy policies take cognisance of one another, or at the very least are not in conflict. Water supply is mostly fixed by nature (allowing for man-made transfers between water basins and for changes in water availability as a result of climate change), whereas energy supply is by design. In some instances water supply can be seen as by design at cost in environmental and economic terms. Bearing in mind what has been said, it is important to assess the demands that might be placed on the country's water resources in the context of changing energy requirements and water availability. This can inform strategic investment in future energy supply.

For sustainable development, South Africa requires secure and reliable water and energy supplies (UN 1998), however, South Africa is the thirtieth most water scarce country in the world (DTI, 2013). While water resources in South Africa are said to offer opportunities for the economy and the much needed employment creation (Odendaal, 2013), limited water supplies necessarily mean that commitment to the establishment and growth of some economic activities will be at the opportunity cost of other economic opportunities.

The imperatives of water and energy provision in the context of a growing economy are factors that should be taken into consideration in designing an energy mix. Hence the motivation for an assessment of the water use of various technologies, and especially in renewable energy (RE) technologies in support of planning for water and energy, and to inform energy and water policy with the vision of facilitating a supportive policy environment.

Previous studies on the water-energy nexus in South Africa include the work of Gulati *et al*; (2013), Carter and Gulati (2014) and Prasad *et al.* (2012). Gulati *et al.* (2013) examine the interconnectedness and interdependence between energy, water and food pricing in South Africa. They consider how energy and water costs influence food prices, with the energy and water focus of their work being primarily from the perspective of energy for water (as opposed to focusing on water requirements for energy production). Their work forms part of a broader study by the World Wide Fund for Nature (WWF), considering the food-water-energy nexus, and to which the study by Carter and Gulati (2014) also contributes. Its focuses is on the food-energy-water nexus, and it briefly mentions the fact that renewable energy has lower water usage requirement. However, the primary focus of their paper is on climate change and the food-energy-water nexus in the context of food security. Prasad *et al.* (2012) describe a modelling framework project (framed within the food-energy-water nexus) being developed for South Africa, which could be used as a tool for policy planning and development. The study presented here differs from the above, since it considers only the water-energy nexus. It specifically focuses on water requirements for energy production, framed within the context of renewable energy.

1.2 Context

In order to consider renewable energy, there needs to be a brief discussion of both renewable and non-renewable (finite) energy sources and their water requirements. This allows for comparisons to be made between renewable and non-renewable sources.

1.2.1 Coal

South Africa can ascribe 92% of its electricity generation to coal (OECD, 2013). Eskom consumes roughly 2% of South Africa's national freshwater resources (334 275 megalitres (ML) (Eskom 2013a; Eskom 2013b) and most of this is associated with coal-fired power stations (Martin & Fischer, 2012). Pulverised coal is combusted to boil water and create steam, which drives electricity-generating turbines.

Water is consumed for many processes in coal mining, from the running of the equipment, dust suppression, washing and processing the coal as fuel, to rehabilitation of the area once the mine is closed. Washing coal contaminates water with sulphur compounds and dissolved iron to create sludge. The sulphur compounds and heavy metals commonly found in coal-bearing rock can contaminate ground or rain water and create a risk of acid mine drainage (AMD). The volume of water required for washing coal depends partly on the quality of the raw coal.

Coal feeds coal-fired power stations and is also used to make liquid fuels. The water impacts associated with these technologies are substantial, as is the impact associated with the mining of coal. The following sections will discuss coal power stations, carbon capture and storage (briefly) as well as coal to liquid fuels.

1.2.2 Synthetic liquid fuels from coal and gas

Liquid fuels can be produced from coal and natural gas (methane). In a typical coal-to-liquid (CTL) process, coal is first gasified to yield syngas, which is then liquefied into hydrocarbons such as gasoline and diesel in a Fischer-Tropsch (FT) process (Mantripragada & Rubin, 2013). Coal is fed into the gasfier in dry or wet form. Thus, the wet gasification process requires water to feed the coal slurry (50% water) into the gasifier (Lu *et al.,* 2012). In South Africa, Sasol and PetroSA produce liquid fuels from low-grade coal using the FT process.

In a gas-to-liquid (GTL) process, natural gas is combined with steam, carbon dioxide or oxygen to form a syngas which then goes through a Fischer-Tropsch process to produce liquid fuels (Rostrup-Nielsen, 2000). Sasol produces syngas from natural gas through three steps (Sasol, 2014):

(a) reforming natural gas with oxygen and steam to produce syngas,
(b) converting syngas to waxy hydrocarbons in a Fischer-Tropsch reactor, and
(c) selectively breaking down the waxy hydrocarbons in GTL diesel, GTL kerosene, GTL naphtha and liquefied petroleum gas (LPG).

South Africa produced an oil equivalent capacity of 150,000 bbl/day through CTL and of 45 000 bbl/day of synthetic fuel through GTL in 2011 (Telsnig *et al.*, 2013).

Nevertheless, the production of syngas via a combination of natural gas and steam requires water.

1.2.3 Carbon capture and storage

The construction of a demonstration plant in South Africa is planned (Creamer, 2013) although in light of the capital investment required to retrofit the existing power stations, it remains to be seen whether this technology will be taken up. Carbon capture and storage technology (CCS) reduces emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). However, this technology reduces energy capacity and increases water consumption at coal fired electricity plants (Wilson et al., 2012).

1.2.4 Conventional oil

By the end of 2011, South Africa had proven reserves of 15 million barrels of oil off-shore in the Bredasdorp Basin and off the west coasts of the country (EIA, 2013). However, these reserves may not be economically viable to extract. Currently, a large proportion of the oil consumed in the country is imported from the Middle East and West Africa and is refined locally.

1.2.5 Natural gas

There are limited reserves of natural gas in South Africa, but significant potential for shale gas resources (about 137.34 billion cubic meters of technically recoverable shale gas resources mostly in the Karoo Basin) (EIA, 2013). However, exploitation of these resources requires drilling and other processes. The country imports most of its natural gas from Mozambique through a pipeline, which is transported to the Sasol Secunda plant for synthetic fuels. Only a small portion is locally produced. Natural gas is used in some of the power plants, in addition to coal.

1.2.6 Solar power

Concentrated solar power

Three concentrated solar power (CSP) production plants, all located in the Northern Cape, have been awarded contracts under the Renewable Energy Power Producer Procurement Programme (REIPPP). Of these, one is a central tower CSP near Upington with capacity of 50 MW, and two are CSP trough plants, one near Pofadder with 50 MW of production capacity, and one near Grobblersdal with 100 MW capacity (Forder, 2013).

CSP plants use mirrors to redirect sunlight on to a specific point to heat a fluid. The heat in the fluid is then used to drive generators and produce power. There are four technical designs used for CSP, the parabolic trough, power tower, linear Fresnel, and the dish Stirling.

Concentrated photovoltaic and photovoltaic panels

Photovoltaic (PV) panels convert sunlight directly into electricity by absorbing protons and releasing electrons. These free electrons are captured on an electrode and result in an electric current, which can be used as electricity (SEA, 2009).

Concentrated photovoltaic technology (CPV) uses optics such as (Fresnel) lenses or curved mirrors to focus large amounts of sunlight (radiation) onto a small area of a photovoltaic cell to generate electricity more efficiently than traditional PV (Soitec, 2013a).

In South Africa, PV is mainly used to provide electricity for telecommunications and lighting in remote areas. It is estimated that roughly 200 000 off-grid PV systems and only 10 grid-connected systems exist. There are currently three concentrated photovoltaic (CPV) farms in South Africa. A pilot project is located in Touwsrivier, with a rated capacity of 82 kWp, one in Johannesburg with a 8.2 kWp and a 480 kWp CPV plant in Hazelmere. A 44 MWp plant is under construction in Touwsrivier and is expected to come online during 2014 (Soitec, 2013b). Some businesses also made installations for their own private consumption (e.g. MTN).

1.2.7 Wind turbines

The generation of electricity by wind energy is through the use of the kinetic energy of air. The average annual energy generated on a wind farm typically varies between 0.05 and 0.25 GJ/m^2 (Blok, 2006).

In South Africa, there is currently only one large scale wind farm in operation (in Jeffrey's Bay in the Eastern Cape). There are also initial plans for other such farms (particularly in the Eastern Cape). In addition there are two small-scale wind farms in operation, viz., Klipheuwel and Darling. As part of the Renewable Energy Independent Procurement Programme (REIPPPP), the Department of Energy has awarded 20-year Power Purchase Agreements (PPA) to a number of wind projects, which will increase the wind power percentage of South Africa's electricity provision in the future. According the Integrated Resources Plan for Electricity 2010-2030 (2010), South Africa plans to install 8.4 GW of wind energy supply by 2030.

1.2.8 Hydroelectricity

Hydropower provides approximately 16% of the total world electricity supply and may be considered a reasonably clean and low-cost renewable source of energy (Hoekstra *et al.* 2011; Mekonnen & Hoekstra, 2012). In contrast, hydropower in South Africa accounts for a very small percentage of total power, at only 2%. Martin and Fischer (2012) note that just under half of this is from run-of-river plants (Gariep (260 MW), Vanderkloof (240 MW) (which are both on the Orange River) and 60% of this is from pumped storage plants (e.g. Drakensberg (100 MW) and Palmiet (400 MW)). There are also two small plants operated by Nuplanet in the Free State province of South Africa, in the vicinity of Bethlehem. A small percentage of our hydropower is imported from Mozambique (Cahora Bassa Dam), Lesotho and Zambia (Eskom, 2011).

There are a number of different methods for generating power using hydroelectricity, the most common and relevant for South Africa being conventional dams (e.g. Gariep Dam in South Africa), pumped storage (e.g. Palmiet pumped storage scheme in the Western Cape of South Africa) and run-of-river schemes (a potential option for small-scale hydro in South Africa).

1.2.9 Bioenergy

Bioenergy is globally the largest, although not always sustainable, renewable energy source, contributing to over 50% of total renewable energy. Bioenergy also contributes over 10% towards final global energy consumption. Biomass is generally derived from natural sustainable organic sources such as decomposing material from plants or animals. This may include wood, agricultural crops and manure, as well as municipal waste (not a natural sustainable source). Bioenergy is formed when biomass is converted and then directly used as fuel or converted into liquid fuel or gases (REN21, 2013). In South Africa, biofuel generation is from waste-from-crops exclusively.

1.2.10 Nuclear power

There are various nuclear technology systems available worldwide. South Africa has only one nuclear power plant in operation, viz., Koeberg Nuclear Power Station, in the Western Cape. A nuclear power plant uses uranium to produce energy, which is dependent on low enriched uranium, rather than fossil fuels, as a source of fuel to produce heat. Heat is generated during the nuclear reaction process of fission. A reactor controls the nuclear process. Energy is generated in the reactor and heats up water, which co-produces steam and drives a turbine. The turbine is connected to a generator, which ultimately produces electricity. The fission process of uranium is used as a source of heat in a nuclear power station in the same way that the burning of coal, gas or oil is used as a source of heat in a fossil fuel power plant.

1.3 Objectives

Energy requirements in the water sector need to be properly examined to establish the overall water supply chain in South Africa. Several alternatives to the energy-intensive water supply chain do exist, including the use of renewable energy sources and local waste-water re-use. However, the impact of deploying renewable energy technologies on water resources need to be considered properly. For example, to allocate water for biofuel production will require a shift in the current water allocation policy. Due to the large gap between water supply and demand, trade-offs in water allocation amongst different users and policy makers are critical. With this in mind, the primary objective of this study is to investigate renewable energy choices for South Africa and their water requirements.

2. Methodology

2.1 Justification

Water scarcity and the drive for optimized use have led to various estimations of the amount of water use (withdrawal or consumption) per MWh (or GJ) of energy output. Various approaches have been adopted in this regard. Some of the more common approaches include water footprinting (Hoekstra *et al.*, 2011), Life-Cycle Assessment (LCA) and various tools designed to help organizations to understand water use, potential impacts and associated risks. There are also a number of methods for assessing broader water use impacts relating to scarcity, stress and human health (Boulay 2013).

Water footprinting is a method for measuring the volume of water abstracted and polluted in the provision of a good or service. This tool can be used to increase awareness of water management challenges and to help consumers make informed purchase decisions (Hoekstra *et al.,* 2011; Morrison & Schulte, 2010). LCA is a systems analysis tool that was designed to measure resource use in order to assess the environmental sustainability of products and services through all components of the value chain (Morrison & Schulte, 2010). Various other tools exist for businesses, for example, to understand their water use and impact and associated water risks. These include the WBCSD Global Water Tool, which helps companies compare their water use, wastewater discharge, and facility information with validated watershed and country-level data. The tool is intended to allow investors and companies from all industry sectors to assess and quantify water-related risks across the globe (WBSCD 2013; WWF-DEG 2011).

This paper considers water use both as withdrawal and consumption, with some qualitative assessment of the water impacts where this information was available. The assessment considered upstream water use (pre-generation) and water use during the generation of energy. It was assumed that water use impacts would be similar for transmission of electricity from different sources and for different liquid fuel types. Downstream water impacts associated with various biofuels could differ, potentially, but for this study the differences have been assumed to be negligible.

The approach therefore in part adopts elements of the footprint methodology (by assessing stages of pre-generation and post generation), however a full assessment of different forms of energy generation was not within the scope of this study. Most of the data has been gathered from secondary sources (literature) and therefore the assessment boundaries are not fully comparable.

An attempt has been made to identify the significant water uses and impacts during pre-generation and generation from the literature and based on interviews with experts. For example, the impact associated with the mining of Rare Earth Elements, as an input into the construction of wind turbines, is included but the impacts associated with the production of the concrete used to build the turbines was not regarded as significant according to the literature and experts. In the same way water use associated with cement used to construct nuclear power stations is not included, as this does not represent a significant water use impact. This approach is intended to identify the most significant water use impacts associated with each energy technology. Assumptions around what can be considered as ‘significant’ water use impacts will be tested during future workshops as part of the larger study.

This study focuses on the water use impacts associated with the pre-generation and generation of renewable energy. However, in order to make comparisons and to contribute to a decision-support tool for policy-makers to use when planning energy investments that consider water impacts, the study includes an assessment of the pre-generation and generation water use impacts associated with non-renewable energy.

2.2 Data collection

The assessment included a review of the available literature. This focused on trying to identify South African specific data on water use impacts associated with the various energy types. A review of international literature was undertaken (not presented here) to provide comparative data or to be used as proxy data where gaps existed in the South African context. An attempt was made to fill these gaps through engaging with local experts. The engagement with experts involved semi-structured interviews focused on accessing quantitative data to fill gaps. In many cases, the investment in renewable energy generation is still in a very early stage of development and thus data were not available. Expert judgement was sought on the likely (qualitative) impacts expected in the South African context relative to international contexts. Future engagements (through project workshops) during later phases of this project will hopefully yield more qualitative data, as some of these projects should be in further stages of development.

2.3 Data processing

Each fuel undergoes several stages during energy production. In a given stage (i^{th} stage) of energy production, water is withdrawn (W_i), consumed (C_i) discharged (D_i) and recycled (R_i) (Fthenakis & Kim, 2010). However, most of the available data in the literature is on water withdrawals and consumption. Consequently, the total water withdrawal (W) and consumption (C) factors over the lifecycle can be computed by using:

$$C = \sum_{i=1}^{i=n} C_i \qquad \textit{Equation 2.1}$$

$$W = \sum_{i=1}^{i=n} W_i \qquad \textit{Equation 2.2}$$

where i = 1, 2, …n, is the number of stages, and S is the summation sign.

Some energy production stages involve several processing options. For example, coal transportation can be through batch (by train) or continuous (such as slurry by pipeline) means. In such cases, the lowest and highest values were identified using Excel. The total withdrawal (W_L) and consumption (C_L) lower-limit factors were calculated from:

$$C_L = \sum_{i=1}^{i=n} C_{i,L} \qquad \textit{Equation 2.3}$$

$$W_L = \sum_{i=1}^{i=n} W_{i,L} \qquad \textit{Equation 2.4}$$

Similarly, upper-limit consumption factors were added to find the upper limit of water usage over the lifecycle of each fuel considered in this study. Bar graphs of these lower and upper values (based on data reported by previous researchers) were plotted for ease of fuel inter-comparison, depending on data availability (see section 4 in this paper).

3. Findings

3.1 Water use in energy production in South Africa

It is reported that the Energy Sector in South Africa uses 2% of the total national water allocation (Wassung, 2010). In addition, coal is currently the main source of electricity in the country. However, disaggregated data on water withdrawal and consumption at specific stages of energy generation is scarce across fuels. Consequently, the coal-water nexus has been investigated more extensively than other fuels.

Conventional energy sources

Some of the reported data for conventional energy is presented in Table 1. It is observed that coal uses more water in plant cooling (1 380-1420 litres/MWh). Using pre-generation values from this table, 263-1646 litres/MWh of water is used between the pre-generation and generation stages. The lower limit is the sum of the minimum values of pre-generation (mining and washing, 183 litres/MWh) and generation (1 380 litres/MWh). For lifecycle usage, Wassung (2010) reported water intensities of 1 534-3 326 litres/MWh), which is comparable to the international consumptive usage (3 460 litres) of water reported by Wilson *et al.* (2012).

South Africa has one nuclear power plant (Koeberg) currently in operation, with an installed capacity of 1 800MW and a capacity factor of 83.1%. Koeberg uses seawater flowing at 80 000 litres/second to cool the condensers (Eskom, 2013a). Using these values, the intensity of water use during generation has been estimated as 192 539 litres/MWh. This value is consistent with findings from other studies. Fthenakis and Kim (2010) reported a water withdrawal value of 120 000 litres/MWh for a nuclear power plant using once-through cooling method. Diesel is also used in backup generators. Water use by dry-cooled generators is relatively low.

Renewable energy sources

There is sporadic data on water usage in renewable energy in South Africa. Gerbens-Leenes *et al.* (2009) report water use for various fuel crops (most of them being food crops). The exploitation of food crops to generate energy creates competition between food and fuel for the same resources. In view of this, the Biofuels Industrial Strategy of the

Table 1: Water usage in energy production by using thermal electric cycles

Fuel	*Energy production stage*	*Water use*[a] *(litres/MWh)*	*Reference*
Coal	Pre-generation, mining& washing	183-226	Martin & Fischer (2012)
	Generation, cooling	1420	Eskom (2013b)
	Generation, dry cooling	100	Eskom (2013c)
	Generation, indirect dry cooling	80	Martin & Fischer (2012)
	Generation, cooling	1380	Martin & Fischer (2012)
Nuclear	Generation, cooling	192 539[b]	Eskom (2013a)
Diesel	Generation, dry cooling, water for purging	0.54	Eskom (2009)

[a] Sources of this data report it as water use, without specifying whether withdrawal or consumption.

[b] This is seawater used at Koeberg nuclear power plant, and so it has negligible impact on the fresh water resources.

Republic of South Africa initially excludes maize from usage as a feedstock in the production bioethanol (DME, 2007). Consequently, agricultural residues from food crops (such as maize husks, stalks and leaves) are predominantly used as a source of thermal energy (DME, 2003). Stone *et al.* (2010) found that production of bioethanol from grain and grain sorghum consumes the highest quantity of water compared to other feedstock.

Data on usage of water in the production of energy from CSP and PV is scarce. Olivier (pers comm., 2013) reported water consumption of 767 000 litres during the construction phase of a 4.5 MW hydro power plant. For wind, Hagemann (pers. comm., 2013) reported water usage of 817 000 litres in the construction phase of a 120MW power plant. The plant would use 3650 litres during operation phase. Assuming a capacity factor of 30%, this yields a water intensity of 0.79 litres/MWh during operation. Over the lifecycle, Wilson *et al.* (2012) reported a water-consumption value of less than 1 litres/MWh.

The analysis to follow has been categorised by fuel type (i.e. coal, oil/natural gas, solar, wind turbines, hydroelectricity, bioenergy and nuclear). As mentioned in the methodology, conventional fuels have been considered in addition to renewable fuels, as this is essential for comparative purposes and in decision-making between renewable and conventional fuel choices. This discussion covers water and water impact for each fuel.

4. Discussion

4.1 Coal power plants

Results from other countries show that wet-cooled thermal power plants withdraw and consume the highest amounts of water on a lifecycle basis. Most of this water is required during the generation stage, for the process of wet-cooling. This shows that more attention needs to be paid to this stage of energy production. However, disaggregated water usage data (stage-by-stage withdrawal and consumption levels) for South Africa is scarce. In view of this, water usage pattern from other countries can be used as an indicator of the situation in this country. More attention is required to curtail the volume of water withdrawal and consumption in the generation stage.

Coal-fired power has a substantial water impact. New technologies may reduce water consumption and impact. In this respect, Eskom has invested in research to use dry processing to purify coal by removing stone – a major source of the ash, sulphur and abrasive components found in coal. This research focuses on removing these components using dry (waterless) techniques to reduce the volume of coal to be transported, improve coal combustion rates and lower emissions (Eskom 2013b; de Korte, 2010).

Eskom has implemented a dry-cooling system in power plants wherever feasible. This is despite the fact that dry-cooled plants are comparatively less energy- efficient than wet-cooled, leading to higher carbon emissions. Moreover, there are higher capital and operating costs associated with dry cooling. Nevertheless, efforts to invest in dry cooling could also have significant water benefits. According to Eskom (2013b), approximately 85% of the total quantity of water supplied to a power station evaporates through these open cooling towers. In contrast, dry-cooling technology does not rely on open evaporative cooling for the functioning of the main systems. Overall power station water use associated with dry cooling is approximately 15 times lower than a conventional wet-cooled power station. This water conservation effort results in an estimated combined saving of over 200 Ml/day, or in excess of 70 000 million litres/annum (Eskom, 2013b).

Matimba Power Station near Lephalale in the Limpopo Province is the largest direct-dry-cooled power plant in the world, with an installed capacity greater than 4 000 MW. It makes use of a closed-circuit cooling system similar to the radiator and fan system used in motor vehicles (Eskom 2013a).

Consequently, water withdrawal and consumption at this plant station is significantly associated with upstream operational stages such as coal mining, processing and transportation.

An additional technology option is indirect dry cooling. This entails the cooling of the water through indirect contact with air in a cooling tower, a process during which virtually no water is lost in the transfer of the waste heat. Eskom is undertaking various other water management projects to reduce water requirements in energy production (Eskom, 2013a). These local efforts are consistent with the observation (from international data) that most of the water is withdrawn and consumed in the generation stage.

4.2 Coal liquefaction

Sasol uses about 4% of the water resources available from the Vaal River System. The water use in operations at Sasol's Synfuels in South Africa is 12 000 litres per tonne of product (Sasol, 2013). Specific withdrawals are not disclosed by Synfuels operations in South Africa (only withdrawals associated with global operations are disclosed).

During 2011 Sasol's main operating facilities at Sasolburg and Secunda set voluntary internal water efficiency targets, which took into consideration site-specific constraints and opportunities. With usage in 2010 as a baseline, Sasol Synfuels at Secunda has a target to improve its water use intensity (volume of water used per tonne of product) by 5% by 2015, while at Sasolburg, Sasol Infrachem is targeting a 15% improvement (Sasol, 2013).

According to Sasol's Water Disclosure Report Submission (Sasol, 2012), "A study has been conducted to determine the relationship between energy usage (and related carbon emissions) and water usage for alternative cooling technologies for the design of new coal to liquid (CTL) and gas to liquid (GTL) facilities." These results will be used to determine the most appropriate cooling technology selection for new facilities, depending on the availability of water at the specific location.

4.3 Carbon capture and storage

The construction of a demonstration plant in South Africa is planned (Creamer, 2013) although in light of the capital investment required to retrofit the existing power stations it remains to be seen whether this technology will be taken up. Carbon capture and storage technology (CCS) reduces emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). However, the technology reduces the energy capacity and increases water consumption (Wilson *et al.*, 2012). CCS technology requires more fuel to produce the same amount of energy as non-CCS technology. Water withdrawal and consumption for CCS power plants is estimated to be between seven and fifty times greater than the water required for non-CCS technology (Wilson *et al.*, 2012). The water impact of CCS is very high.

4.4 Nuclear power

Koeberg Nuclear Power Station has three different water systems, known as the primary, secondary and tertiary circuits. The three water systems are used to cool down the heat produced by the fission energy process. The primary water system is a closed system and is radioactive. No water consumption is involved in this system. The secondary and tertiary systems use seawater to produce steam to turn the turbines (Eskom, 2013a). Water use for a nuclear power station such as Koeberg is extensive (mostly seawater), but uses a negligible volume of fresh water. It is presented here for completeness.

Water is required at a power plant to cool the system and also to condense the low-pressure steam and finally to recycle it. When the steam in the internal system condenses back to water, the excess heat, which is removed from the system, needs to be recycled and transferred to either the air or to a body of heat. At most coal-fired power stations, the indirect method is used to remove the excess heat. The system uses water and by releasing steam into the air using large cooling towers, the excess heat is removed from the system.

The Koeberg Nuclear Power Station is built adjacent to an abundant water source (the ocean) and hence uses the direct cooling method to cool down its system. This method uses water only once to cool down the internal water system and circulates the water back into the ocean at an increased temperature level. Water consumption is marginal, with a small proportion the withdrawn water being consumed. The small amount of water consumed and/or lost refers to the evaporation that occurs when the water circulated back into the ocean and being a few degrees warmer than the ocean temperature (World Nuclear Association Cooling power plants: accessed 15 October 2013). The use of seawater reduces the competition for fresh water. Nevertheless, the elevated temperature of the discharged water may affect the ecosystem at the discharge point.

4.5 Oil and natural gas

Extraction of oil by hydraulic fracturing involves pumping a mixture of water, sand and other additives into the ground, thereby creating cracks. The oil is then forced out through these cracks. In addition, water is used in oil or gas-fired thermal electric generators that are wet-cooled. Most of the water used in the production chain of oil/gas-fired thermoelectric power is during generation.

Hydraulic fracturing contributes to contamination of ground water (Kharak *et al,*. 2013). Some of the contaminants include methane, benzene and gasoline and diesel range organics. In some cases, well-fed tap water has become flammable due to the presence of these contaminants (Wilson *et al.,* 2012). The high demand of water for wet cooling puts stress on water resources.

For natural gas, there have been environmental concerns regarding water usage and hydraulic fracturing in the Karoo area. It has been estimated that about 10-15 million litres of water may be required to drill one well (Sovacool, 2014). However, in light of the fact that the Karoo area is an arid environment, water will have to be sourced from a distance. In addition, water is used in gas-fired thermal electric generators that are wet-cooled. Most of the water used in the production chain of oil/gas-fired thermoelectric power is during generation (up to 5 850 MWh/litre), (Wilson *et al.,* 2012).

4.6 Concentrated solar power and photovoltaics

Concentrated solar power (CSP) plants use water in the resource extraction and the manufacturing of the components in the collector. Most of the water used during manufacturing is linked to the heating, ventilation and air-conditioning (HVAC) system of the manufacturing plant. The parabolic trough, power tower and linear Fresnel technologies can use wet, dry or hybrid cooling systems. The dish Stirling does not require a cooling system (the heated fluid is hydrogen).

CSP plants using steam cycles require cooling to condense the steam exiting the turbines. In this study, it has been found that these plants withdraw 500-5 000 litres/MWh and consume 300-5 000 litres/MWh, which is in agreement with finding from other studies (2 000-3 000 litres/MWh reported by IEA-ETSAP & IRENA (2013).

Dry (air) cooling is an option for areas where water is a constraint, but dry (air) cooling is less efficient than wet cooling and this reduces the capacity (or output) of the plant. Compared with wet cooled CSP plants, electricity production is typically reduced by 7% and the capital cost increased by 10% in dry cooled plants (IEA-ETSAP & IRENA 2013). The water impact of CSP plants is very low.

Water is used in the production of PV-cells. The water use can be divided into two groups of users. Firstly the manufacturing plant and its infrastructure, for example water use for HVAC, sanitary use, and landscaping. The second group is the manufacturing process itself where standard and highly purified de-ionized water is used to manufacture PV cells (Williams, 2011). The water use is associated with removing chemical residues from equipment and rinsing of substrate wafers and panels.

A study done by Sinha *et al.* (2013) states that half of the life cycle water withdrawal is associated with the manufacturing of the module and the water consumption during the manufacturing of a CdTe PV-cell is a quarter of the water withdrawal. The water consumption is linked to cooling tower evaporation and site irrigation.

Water is also used during the project construction, but with no documented figures easily accessible. The water use during generation is linked to the cleaning/washing of the PV-panels. International literature suggests figures of 15 litres/MWh for CPV and PV (NREL, 2002; Fthenakis & Kim, 2010). How often cleaning occurs in SA is not yet quantified. It is likely to be dependent in part on the (climate) area where the system is installed.

4.7 Wind power

Wind power does not use water in the acquisition or supply of energy *per se*. It does, however, use water in the refinement of the rare earth minerals required for the production of the turbines. Rare earth metals are a group of 17 metals that used to be considered a by-product of mining but are now seen as an important component of many “green technologies” such as electric cars, solar panels, and wind turbines. They are not so much rare as mixed up with other rare earth minerals, making them at times uneconomical to mine. The magnets used in wind turbines have an important rare earth component known as neomycin. Presently, neomycin is imported almost entirely from China, although there are rare earth element sources available in the USA, South Africa, and elsewhere. A large wind turbine (approximately 3.5 MW) generally contains 600 kg of rare earth metals.

Wind energy does not require water for its generation (assuming the land used is still offered for other uses such as agriculture) (Gleick, 1994; Martin & Fischer, 2012), Water use for the turbine construction phase has been deemed negligible (Gleick, 1994). There is also likely negligible water use in the washing or the turbine blades from time to time. The water use in the production of rare earth elements such as neomycin does not impact on water use in South Africa, but they do impact on the water footprint globally.

4.8 Hydroelectricity

No additional water is used in acquiring or supplying of hydropower. However, a substantial quantity of water is needed to ensure a constant fuel supply source (Pegram *et al.* 2011). Some suggest that no water is used in the process of hydropower generation, since the water used in generation is returned to the water resource and it hence qualifies as instream water user. Others argue that evaporation losses associated with the hydropower plant are significant and that hydroelectricity is a significant consumer of water (Hoekstra *et al.,* 2011; Mekonnen & Hoekstra 2012).

One of the seminal papers that have considered water and energy, making reference to hydropower water consumption is that of Gleick (1994).

Important omissions in this paper are previous environmental evaporation and negligibilty of seepage (Pegram *et al*., 2011). Gleick (1994) estimates a range of hydropower evaporation values, varying from a minimum of 0.04 m^3/MWh, to a maximum of 210 m^3/MWh, with an average of 17 m^3/MWh.

In South Africa, evaporation rates vary spatially across the country (see Schulze (2008) to some degree mirroring the annual rainfall rates spatially too. The highest rates are in the North West (NW) and central regions of the country, decreasing eastwards towards the east coast. Such spatial evaporative losses are important to consider in terms of future planning for hydropower dam placements. Nonetheless, when considering evaporation losses, the size of the reservoir (a deep reservoir with a lower surface area will have less evaporative loss) is more important than the climate itself.

Mekonnen and Hoekstra (2012) consider the blue water footprint of hydroelectricity, linking this to the evaporation loss associated with the artificial reservoirs created behind hydroelectric dams. In their study, they calculated the blue water loss through a series of equations and assumptions, and came up with a figure of 90Gm^3yr^{-1}. In perspective, this equates to 10% of the blue water footprint of global crop production in 2000, which they find to be relatively large when compared to other renewable sources of electricity (Mekonnen & Hoekstra, 2012).

Pegram *et al.* (2011) point out that Mekonnen and Hoekstra (2012) do not consider evapotranspiration of natural vegetation, in their interpretation of water consumption. When considering evaporation losses in terms of hydropower, Pegram *et al.* (2011) argue that it is net evaporation loss that needs to be considered, as opposed to total evaporation loss. Net evaporation loss refers to the difference the evaporation deviates from a natural reference condition (e.g. natural vegetation) (Pegram *et al.,* 2011). This, they believe will reflect a more accurate picture. Other studies in different environments e.g. in New Zealand (Herath *et al.,* 2011) highlight the need for taking the local environment into consideration, since their values are notably lower than the global averages presented by Gleick (1994).

In addition to considering evaporation losses, it is important to remember that hydropower is generally responsible for changing the flow regime (Pegram *et al.* 2011). This in turn may impact on the environment as well as water availability to users downstream. Conceptually it is also worth noting that a nominal amount of water is used in constructing a hydropower plant, albeit negligible (Pegram *et al.* 2011).

4.9 Bioenergy

Water use in the production and application of bioenergy varies. Dominguez-Faus *et al.* (2009) estimated that ethanol production from corn requires from 2 270 000 to 8 670 000 litres/MWh, whilst soybean based biodiesel pre-generation and generation utilizes between 13 900 000 and 27 900 000 litres/MWh compared to the 10-40 litres/MWh required for petroleum extraction.

Closer to home, de Fraiture *et al.* (2008) indicated that South Africa uses approximately 416 million litres of water to produce sugarcane for bioethanol production per annum, which is equivalent to 9.8% of total irrigation that is directed at biofuels production. This is a significant amount for a water-stressed country.

The global production of bioethanol from grain and grain sorghum consumes the highest quantity of water compared to other feedstock. In contrast, sugar cane appears to have the lowest water footprint in ethanol production. Stone *et al.* (2010) explain this wide disparity by arguing that only the grain in the corn is used to produce ethanol, whilst the rest of the crop, that is, the lignocellulosic materials (i.e. leaves, stalk and stem) are not utilised in the process. Furthermore, the authors indicate that sugar cane and corn have different photosynthetic processes, which could, in part, explain their dissimilar water requirements aside from the obvious fact that they are two different crops (Stone *et al,.* 2010). Soybean is also water inefficient in that it requires very high quantities of water for irrigation and even more for the actual production of biodiesel. To further attest to this, some commentators contend that over 180 000 litres of water would be required to generate sufficient amounts of biodiesel from soybean to power a household for a month (Jones, 2008).

More disaggregated and updated (recent) data is required for water usage in biofuels production in both the global sphere and South African context. For instance, no data could be identified for the processing phase of ethanol production using sugar cane *viz.* cane washing, condenser multi-jet in evaporation and vacuum, fermentation cooling and alcohol condenser cooling, barring an indication that in 1997 all this was estimated to consume 21m^3/ton and that this has reduced over time to 1.83 m^3/ton in 2004 (Goldemberg *et al.* 2008).

While all the authors concur that in some regions, rainfall meets the irrigation requirements of the production of biofuel feedstock, they readily admit that the production of biofuels is and will continue to compete for limited water stocks in many countries, including the USA. Needless to say, this will put additional pressure on limited natural resources for agricultural production (Dominguez-Faus *et al.,* 2009; de Fraiture *et al,.* 2008; Stone *et al,.* 2010). In the case of the USA, this is exacerbated by the Government requirement to produce 57 billion litres of ethanol from corn by 2015 (de

Fraiture *et al.,* 2008). On the other hand, the strategy on biofuels in South Africa initially excludes the use of maize to produce bioethanol (DME, 2007), thereby reducing the energy-food competition for natural resources.

All this points to the fact that while a low carbon economy is important, it comes with a significant price tag for water resources – "green energy for blue resources" as de Fraiture *et al.* (2008) point out in the title of their paper.

5. Conclusion

Water usage in the production of energy from conventional and renewable fuels has been explored. Data have been acquired through a combination of a desktop study and expert interviews. Water withdrawal and consumption levels at a given stage of energy production have been investigated. Results show that, for South Africa, there is limited data on all aspects of water usage in the production of energy, accounting in part for the significant variations in the values of water intensity reported in the literature (with some approximations). It is vital to take into account all aspects of the energy life cycle to enable isolation of stages where significant amounts of water are used.

Conventional fuels (nuclear and fossil fuels) withdraw significant quantities of water (this is seawater in the case of nuclear) over the life-cycle of energy production, especially for thermoelectric power plants operated with a wet-cooling system. The quality of water is also adversely affected in some stages of energy production from these fuels. Hydro is by nature the most water-intensive source of energy (among all the energy sources covered in this work). However, it is limited in terms of its water consumption. Similarly, biomass is water intensive, but this water would have been used in the production of crops regardless. Thus, these two renewable energy sources have a perceived high impact on water resources. It should be noted, however, that in South Africa biofuel generation is by means of waste-from-crops only. Solar photovoltaic (PV) and wind energy exhibit the lowest demand for water, and could perhaps be considered the most viable *renewable* options in terms of water withdrawal and consumption. Moreover, the observed water usage in these renewable energy technologies is predominantly upstream.

It would be beneficial to consider relevant renewable energy case studies for water consumption and withdrawal in South Africa. This would allow for water consumption and withdrawal comparisons between fuels to be made. The two fuels that would perhaps be most worthwhile in terms of case studies, are wind and solar. The Darling Wind Farm (and proposed extensions), or one of the new wind farms proposed for the Eastern Cape or West Coast of South Africa, would be interesting to study. In terms of CSP the two plants being constructed *viz.* Kaxu Solar 1 and Khi Solar 1 would be beneficial to follow up on. The Aquilla CPV plant in Touws River would also be worthwhile considering

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