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# Renewable energy choices and water requirements in South Africa

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## Key points

- There is limited data on all aspects of water usage in the energy production chain.
- Values of water intensity reported in the global literature vary significantly.
- Wet-cooled conventional thermal power plants demand a significant amount of water over the life-cycle of energy production.
- Solar PV and wind exhibit the lowest demand on water.

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# Executive summary

South Africa (SA) is an arid country, where water supply is often obtained from distant sources. There is also 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 (major greenhouse gas). In addition, fossil fuels are getting depleted, thereby decreasing energy security. Consequently, the international community has initiated various interventions, including the transformation of policy and regulatory instruments, to promote sustainable energy.

In view of this, SA is making policy and regulatory shifts in line with the 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 renewable energy choices and water requirements in SA.

Data was 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 at international and national levels. Most of the data was collected from secondary sources (literature) and therefore the assessment boundaries are not fully comparable.

Results show that there are 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 global literature. It is vital to take into account all aspects of the energy life cycle to enable isolation of stages where substantial amounts of water are used.

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 energy options in terms of water withdrawal and consumption.

# 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. It is worth noting that, while the water energy nexus is part of the wider water-energy-food nexus (relevant in the context renewable energy technologies for biofuels, and in some cases hydropower), this report focuses on water requirements for energy production. The energy usage associated with water supply and sewerage disposal falls outside the scope of the present investigation.

The production of electricity may consume a substantial quantity of water in the processing and transportation of raw materials, plant construction and the generation of power. 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 policy. Climate change is expected to put added strain on water provision due to projected changes in seasonal and regional temperature and patterns of precipitation (Hoekstra *et al.* 2011; Wilson *et al.* 2012).

South Africa (SA) has a recent history of energy shortages, electricity blackouts in 2007 and 2008, and 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 the current production methods will increase the energy demand for water and may involve some 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.

SA 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 9 water management areas. 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 energy 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 the energy supply from the current primary reliance on coal-fired electricity, to an energy mix in which a third is generated from renewable resources (DoE 2010). To meet this goal, the government is currently offering incentives for investment in renewable energy technologies under 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. As water supply is (mostly) locality-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; 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.

Secure and reliable water and energy supplies are required for sustainable development (UN 1998), but SA is the thirtieth most water scarce country in the world (DTI 2013). While water resources in SA 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 others. So, 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 energy technologies, and especially 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 conducive policy environment.

## 1.2 Water for energy concepts

Before assessing water for energy, there are some concepts to consider. These concepts are outlined below.

### 1.2.1 Water withdrawal and water consumption

The water requirement for energy provision can be distinguished as water withdrawal or water consumption. The water withdrawal is the volume of water extracted from the water source and so it becomes unavailable for alternative use. This water may not be returned to the source. The water consumed is the volume that is permanently removed from the water source or undergoes a change in quality so that it is no longer considered useful as a supply of water. It is not discharged as useful water back into the watershed.

Pegram *et al.* (2011 p. 6) describe consumed water as equal to "the evaporative loss in a production (i.e. the difference between the water received and the water returned from the facility), any water contained directly in the product (usually a relatively small portion) and water used and made unavailable for future uses (e.g. polluted water) during production". In the context of energy supply the proportion of water consumed to that withdrawn varies widely, as will be described further in the report.

### 1.2.2 Water used for cooling

Cooling is required in thermal power plants where a working fluid (such as water) is heated to drive an electricity-generating turbine. In a steam turbine, water is used as a working fluid. The steam needs cooling after driving the turbine (Figure 1.1). These power plants can utilize wet, dry or hybrid systems of cooling. The choice of a cooling system for the waste heat exchanger determines the amount of water required.

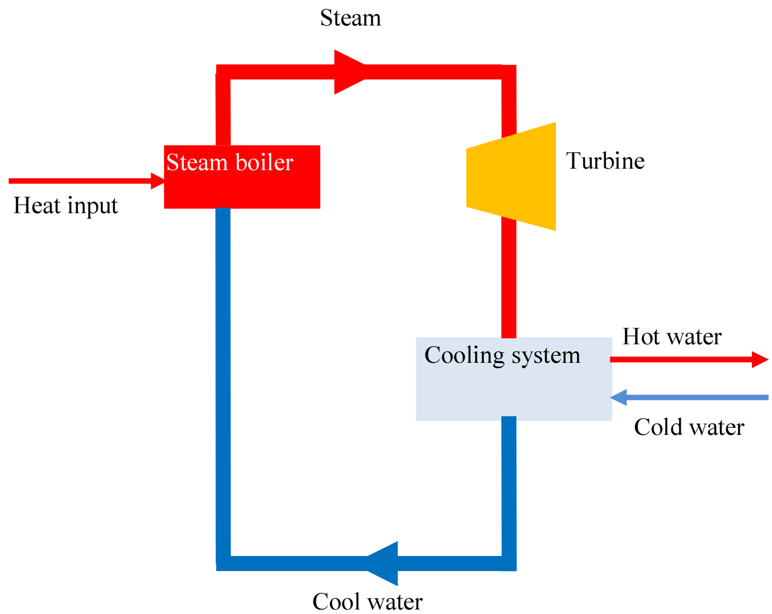



**Figure 1.1: Steam power plant with a wet-cooling system.**

***Wet cooling***

Wet cooling systems use water for heat exchange from the steam turbines. They are the most energy-efficient cooling systems, but they use the highest quantity of water. There are three types of wet cooling systems: the once-through, recirculating and pond systems. In addition, a wet-cooled power plant comprises two systems of water. The first is the water system that is heated to create steam to drive a turbine. The steam is condensed by the cooling system (after driving the turbine) so that the condensate (cool water) can be re-used as a liquid working fluid. The second water system is for removal of waste heat from the power plant to the ambient environment.

***a) Once–through cooling***

Water is extracted from the water source (a river, dam or the sea) and circulated in pipes to absorb heat. It is then released from the power plant at a higher temperature. Once-through cooling requires abundant water and a reliable supply. The altered temperature of the water released may have an impact on the local ecosystem. There is very little evaporation and little change to the water quality as the water passes through the cooling system. This method of cooling has the lowest water consumption, but the highest water withdrawal.

*b) Re-circulating*

Re-circulating cooling systems extract water from the source. After the water is circulated in pipes to condense the steam, it is cooled down and re-used as cooling water. Cooling towers are commonly used to release heat from the cooling water into the atmosphere and some of the water is lost in evaporation (consumed). Re-circulating cooling systems withdraw less water than once-through systems (only replacing evaporated water), but this method of cooling has the highest water consumption.

*c) Pond*

Pond cooling systems extract water from the source and store it in an open reservoir or pond. Water is then drawn from the pond and run through pipes to extract heat from the steam used to generate the electricity, before being released back into the pond. The warm water in the pond then releases the heat to the atmosphere predominantly through the evaporative mode of heat transfer. The amount of water withdrawn is the volume diverted to the pond and the water consumed is the water that evaporates to the atmosphere. The volume of water withdrawn for a pond cooling system depends on the size of the pond. The volume of water consumed in pond cooling is less than in re-circulating but more than in once-through systems.

***Dry cooling***

Dry cooling systems use (withdraw or consume) less water, if any, than wet cooling systems. However they are less energy-efficient and so they use more fuel to produce the same amount of electricity. In the case of fuel combustion, this results in increased emissions. If the water is consumed in the preparation and processing of fuel, then net water savings gained by choosing a dry cooling system are reduced.

***Hybrid cooling***

Hybrid cooling systems combine dry and wet cooling methods to eject waste heat to the ambient environment. Water requirements are intermediate between the two techniques, depending on the ratio used. If most of the waste heat is removed by the dry technique, then the system requires a low quantity of water.

From the description of the cooling methods, there are evidently trade-offs in the choice of a cooling method. The most appropriate choice will depend on the water availability and the impact of the withdrawal and consumption requirement, on cost (directly related to the cooling method and indirectly related, say in the fuel requirement) and on the related environmental impacts, for example of increased air pollution. Table 1.1 below illustrates some of the trade-offs between water withdrawal and consumption, and the cooling efficiency (and hence of some of the related costs) of various cooling systems.

**Table 1.1: A comparison of the water withdrawal, consumption and cooling efficiency of various cooling systems**

| *Cooling* | *Water withdrawal* | *Water consumption* | *Cooling efficiency* |
|---|---|---|---|
| **Wet – once through** | High | Low | Good |
| **Wet – recirculating** | Low | High | Medium |
| **Wet –pond** | High | Low | Medium |
| **Dry** | None | None | Poor |

### 1.2.3 Water accounting – appropriate metrics

An appropriate method for water accounting is required in order to consider water use (withdrawal and consumption) in energy technologies. Various methods for the estimation of the amount of water used per megawatt hour (MWh) or gigajoule (GJ) of energy output have been developed. Previous studies have endeavoured to estimate the direct water consumption in the generation process and also in supply chains (Gleick 1994; Torcellini *et al.* 2003; Gerbens-Leenes *et al.* 2009). In a comparison of water use estimates, it is important to note whether volumes are reported for water withdrawal or consumption.

This study compares the water requirements of various energy technologies. Some stages within the complete process of energy provision may be fixed in locality and thus more relevant in terms of their demand for water. The water requirement during other stages might be relocated, albeit at some cost, even outside of a water-constrained area, or outside South African borders. An example of this is the water embedded in the building materials or components for a technology or power plant. The water requirement of the 'fixed locality' stages of energy provision are most relevant for water resource management and hence for policy around the water energy nexus. The method of water accounting should thus be applicable to distinct stages of production.

The water requirements of energy technologies vary widely in terms of their water withdrawal and their water consumption. The volume of these separate water requirements has implications on the socio-economic and ecological environment dependent on the area the water is abstracted from. To reflect on the impacts of water used for energy, the water accounting method should be applicable with the distinction of water withdrawal and water consumption.

***Life cycle analysis***

A life cycle analysis (LCA) can be used to investigate and evaluate the environmental impacts through all stages of the provision of a service or product. It is a useful framework to conceptualise the impact from 'cradle to grave'. LCA tools include the ISO 14000 series and the United Nations Environment Programme (UNEP) LCA tool. The LCA is useful for considering the aggregate impact across all stages within a production cycle. It is not useful to investigate a bounded stage within production, nor of impacts within a geographically bounded area.

***Virtual water***

The concept of virtual water was developed to describe flows of water, not in the conventional fluid water body sense, but as water embedded in traded products. The concept is useful for discussions of how trade has the equivalent effect of water flowing in or out of an area of water scarcity. The concept of virtual water is especially useful for thinking about the impact of trade on water security, but not for estimating water use within a locality (Hoekstra *et al.* 2011).

***Water footprint***

The concept of a water footprint was developed by Chapagain and Hoekstra (2004). They describe its three components as green, blue and grey virtual-water. Green water is supplied by precipitation, blue water is abstracted from ground water or surface water or water bodies, and the term grey water refers to water that has been polluted by human activity, or more specifically as "…the amount of water needed to dilute pollutants emitted to the natural water system during the production process to the extent that the quality of the ambient water remains beyond agreed water quality standards" (Hoekstra & Chapagain 2008). These terms provide a useful lens to consider water withdrawal versus water consumption. Withdrawal of water is blue water and water consumption is in part grey water.

The water footprint technique is appropriate for comparison of water use between similar stages of production. . It focuses on volumes of water withdrawal and water consumption per unit of energy produced, and on the stages of water production relatively fixed in locality (by the abstraction or growing of fuel, or at the point of fuel processing or energy generation). However, it does not describe the water lost through evaporation. One might argue that evaporated water remains in the hydrological cycle, where the rate of evaporation is high, for example in a pond cooling system, or in the retention of water in a hydroelectric dam. Nevertheless, evaporated water is, by earlier definition, consumed because it is unavailable for use in the vapour state.

In some of the stages of energy production, water use is bound to a locality (area or region). For example, a wind turbine may be manufactured in Chine and imported into South Africa. The water usage associated with manufacturing of the turbine would therefore be bound to China. Consequently, this report uses a water accounting method similar to that of the water footprint.

### 1.2.4 The water cycle in stages of energy production

Water is used for energy production in the abstraction, growth and preparation of some fuels as well as in some technologies for power generation. Water is also used in the raw materials for plant infrastructure, in the making of the components, and the building of power generating infrastructure. However, these materials can be imported from any location. This volume of water will vary widely, not only with the technology, but also with the materials used and even the infrastructure design. This water use is not limited to any water catchment, water management area or local authority.

The stages of energy production that are fixed to a location are the stages of fuel acquisition, production and processing, and where the energy is generated. The water footprinting technique can be used to compare the water withdrawal and consumption across various energy technologies, specifically for the stages of fuel acquisition and preparation, and the stage of generation (Fthenakis and Kim 2010). Water is withdrawn ($W_i$), consumed ($C_i$), recycled ($R_i$), and discharged ($D_i$) at any given stage of the energy production process (Figure 1.2).

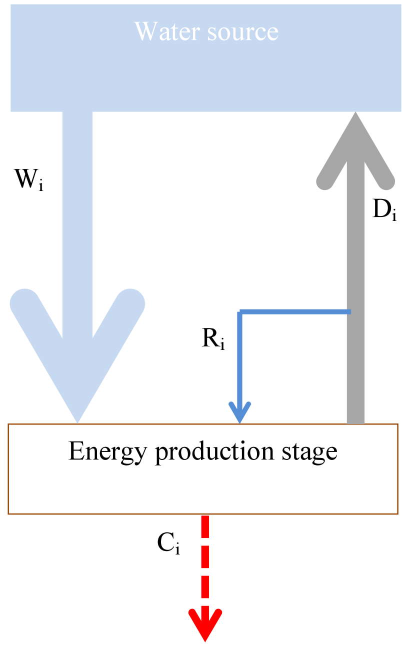



**Figure 1.1: The water use in a given stage of the energy production process.**

***Water impacts of energy provision***
The impact of water use for energy provision varies not only with the volume withdrawn and consumed, and with the quality of water discharged into the water cycle but also with the specific context of the environment and community reliant on the water source. Put differently, the economy or ecology within a watershed may be more or less resilient to a reduction in the available water volume or quality. A small water withdrawal or consumption in a water scarce locality or in an area in which the economy is highly reliant on nearly all the available water supply will be vulnerable to negative impacts from a small reduction in water supply. Conversely, in an area where the fresh water supply considerably exceeds the needs of the economy or local environment, a substantial water withdrawal or consumption may have negligible impacts. In light of the context specific nature of the impacts of water withdrawal and consumption (in terms of both environmental and socio-economic impacts), this report makes limited comments on the impacts of water use. Impacts are referred to as being consistent with the amount of water withdrawn or consumed (high water use inferring high impacts), although it is recognised that the impacts should be considered on a case-by-case basis.

## 1.3 Context

### 1.3.1 Coal

South Africa can ascribe 92% of its electricity generation to coal. There are seventeen coal-fired power stations in operation and there are also a further two being constructed (Medupi in Limpopo and Kusile in Mpumalanga (Colvin *et al.* 2011). Eskom consumes roughly 2% of South Africa's national freshwater resources (334 275 megalitres (ML) (Eskom 2013a; Eskom 2013b) and most of this water 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 used in many coal mining processes: operation of the equipment, dust suppression, washing and processing the coal as fuel, and rehabilitation of the area once the mine is closed. Coal washing 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). AMD is becoming an increasingly serious concern in South Africa and coal mining contributes to this problem (McCarthy 2011). The volume of water required for washing coal depends partly on the quality of the ore.

Coal feeds coal-fired power stations and is also consumed in the production of liquid fuels. The water impacts associated with these technologies are substantial, as is the impact associated with the mining of coal. The sections below will discuss coal power stations, carbon capture and storage (briefly) as well as coal to liquid fuels. Integrated Gasification Combine Cycle (IGCC) will not be considered beyond mentioning that water is consumed in gas processing by evaporation and contamination. Data is scarce in terms of isolating the ICGG technology in particular.

### 1.3.2 Coal to liquid fuel (CTL)

In a typical CTL process, coal is first gasified to yield synthetic gas 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 into the gasifier. In South Africa, Sasol produces liquid fuels from low-grade coal using the FT process.

Sasol is an integrated energy and chemical company based in Johannesburg. Sasol Synfuels delivered production volumes of 7 443 million tons (mt) in the 2013 financial year (Sasol 2013a).

Sasol Synfuels operates the world's only coal-based synfuels manufacturing facility, located at Secunda. It produces petrol, diesel, liquefied petroleum gas, chemical feedstock and industrial pipeline gas. The company receives coal from five mines in Mpumalanga. After being crushed, the coal is blended to obtain an even quality distribution. Electricity is generated by both steam and gas and is used to gasify the coal at a temperature of 1300°C. This produces syngas from which two types of reactor – circulating fluidized bed and Sasol Advanced Synthol™ reactors – produce components for making synthetic fuels as well as a number of downstream chemicals. Further products from the gasification process are ammonia from gaseous water and various grades of coke from tar oil (Sasol 2013b).

### 1.3.3 Carbon capture and storage (CCS)

Carbon capture and storage is a process in which waste carbon dioxide ($CO_2$) from large point sources (eg. coal power plants) is trapped and transported to storage facilities. The CCS technology reduces the emissions of $CO_2$, methane ($CH_4$) and nitrous oxide ($N_2O$) into the atmosphere. However, the technology decreases the energy capacity and raises water consumption (Wilson *et al.* 2012).

The construction of a CCS 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.

### 1.3.4 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). Nevertheless, 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. The consumption is about 450 000 barrels (bbl) per day of which 255 000 barrels are imported. The balance comes from synthetic fuel from coal produced by Sasol, and natural gas from Mossgas (Davidson *et al.* 2006). Gasoline and diesel fuels are locally produced from coal and natural gas. It should be noted that South Africa has the second largest capacity for crude oil refining (484 547 bbl/day) in Africa and the country plans to increase its domestic refining capacity (EIA 2013).

A portion of the oil is used in the electricity generation industry, in addition to coal. Table 1.2 shows Eskom power plants that are operated on gas and liquid fuels.

**Table 1.2: Eskom gas and liquid fuel turbine stations in South Africa**
*Source: EIA (2013)*

| Power station | Capacity (MW) |
|---|---|
| Acacia | 171 |
| Ankerlig | 1327 |
| Gourikwa | 740 |
| Port Rex | 171 |

### 1.3.5 Natural gas

There are limited reserves of natural gas in South Africa, but significant potential for shale gas resources (about 137,34 billion cubic metres of technically recoverable shale gas resources mostly in the Karoo Basin), EIA (2013). However, exploitation of these resources requires exploration involving drilling and other processes. Natural gas is locally produced from the maturing offshore F-O field and South Coast Complex fields, and it is sent to the gas-to-liquid (GTL) plant in Mossel Bay through an offshore pipeline. The country imports most of its natural gas from Mozambique through a pipeline and transported to the Secunda plant for synthetic fuels. Natural gas is used in some of the power plants, in addition to coal. These are mostly standby thermoelectric generators (wet or air-cooled).

### 1.3.6 Solar power

***Concentrated solar power***

Three concentrated solar power (CSP) production plants, all located in the Northern Cape, have been awarded contracts under the 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 focus and convert solar radiation into heat which is transferred to a working fluid. The heat in the fluid is then used to drive the generator and produce power. There are four technical designs used for CSP, the parabolic trough, power tower, linear Fresnel, and the dish Stirling. Most CSP-plants use similar technologies to generate electricity and use one of the following 3 collector technologies (SEA 2009).

*a) Solar trough*

A solar trough collector consists of a linear trough–shaped parabolic collector, which moves around a single axis to follow the sun. Solar radiation is concentrated onto an insulated absorption tube in the centre of the collector and runs the full length of the collector. The collector uses a carrier fluid to transport the collected heat to a storage medium or the turbine (SEA 2009).

*b) Power tower*

The power tower uses many mirrors, which all track the sun and move on multiple axes to focus the sun's radiation onto a single receiver point. Like the solar trough, the power tower uses a working fluid to transport the heat to a storage medium or a turbine.

*c) Parabolic dish*

A parabolic dish system consists of one or more parabolic dishes, which concentrate the radiation into a single point. This point can hold a collector, which holds a carrier fluid or a sterling engine, which is coupled to a dynamo.

***Concentrated photovoltaic and photovoltaic panels***

Photovoltaic (PV) panels convert sunlight directly into electricity by absorbing photons 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 (Fresnel) lenses or curved mirrors to focus large amounts of solar radiation onto a small area of a photovoltaic cell to generate electricity more efficiently than traditional PV (Soitec 2013b). The greater efficiency comes from the type of photovoltaic cells used in CPV. CPV systems track the position of the sun, which augments the cost of the technology. However, the increased efficiency of CPV offsets the additional cost of cooling and two-axis tracking required to maintain high insolation (Soitec 2013b).

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 in 2014 (Soitec 2013a). It is expected that more grid-connected PV-power plants will be commissioned through the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

### 1.3.7 Wind turbines

The generation of electricity by wind energy is through the use of the kinetic energy of the air. A wind turbine extracts energy from moving air and converts it to electrical power. The collection of wind turbines in the same location is a wind farm. 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 are currently no large scale wind farms in operation, although there are initial plans for such farms (particularly in the Eastern Cape). Currently, there are two small-scale wind farms in operation, viz., Klipheuwel and Darling. As part of the REIPPPP, the Department of Energy has awarded 20-year Power Purchase Agreements (PPAs) 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.

### 1.3.8 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 the 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). In addition, 4% of hydropower is imported from the Cahora Bassa Dam in Mozambique, and limited imports from Lesotho and Zambia (Eskom 2011).

Hydroelectricity is generated by harnessing potential energy in the flow of water to drive electricity turbines. Rivers and streams may be re-directed and dams constructed to feed hydro generators. There are a number of different methods for hydropower generation, 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 (this is a potential option for small-scale hydro in South Africa).

### 1.3.9 Bioenergy

Bioenergy is globally the largest renewable energy source, contributing to over 50% of total renewable energy. Bioenergy also contributes over 10% towards final global energy consumption. Biomass is derived from natural sustainable organic sources such as decomposing material from plants or animals. It also includes wood, agricultural crops, municipal waste and manure. Bioenergy is formed when biomass is converted and then directly used as fuel or converted into liquid fuel or gases (REN21 2013).

Technology application varies depending on the source content. Biomass can directly be used as a co-fired energy source during electricity generation. During this process traditional fossil fuels such as coal or natural gas together with biomass can be incinerated to generate heat for electricity generation. It can also be traditionally applied by combusting natural biomass in home appliances such as coal or gas stoves. Furthermore, biogas technologies include anaerobic biogas digesters that generate gas for home cooking and heating purposes. The production of ethanol to be used in bio-diesel also goes through various industrial processes, but the final technology application is in vehicles (EREN 2000).

### 1.3.10 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. The plant was designed and built by Framatome (now Areva) and commissioned in 1984-85. The Koeberg nuclear plant has two 900 MWe pressurised water reactors technology systems totalling 1 800 MWe (World Nuclear Association 2013).

A nuclear power plant uses a uranium to produce energy. It cannot, however be compared to fossil dependent plants such coal, oil and gas fired power stations. The energy generated by a nuclear plant is dependent on low enriched uranium, rather than fossil fuels, as a source of fuel to produce heat. Heat is generated during a nuclear reaction process called "fission". Fission is the process of splitting the nuclei of atoms into smaller particles such as protons, electrons and neutrons.

A reactor has components for controlling the fission process to avert excessive heat generation. 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.

Producing energy with the fission process is far more efficient compared to other processes using fossil fuels. For example, approximately 44 GWh of electricity are produced from one tonne of uranium. To produce the same amount of electrical power from fossil fuels, the process would require the burning of over 20 000 tonnes of black coal or 8.5 million cubic metres of gas (World Nuclear Association, Nuclear Fuel Cycle Overview 2013).

## 1.4 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 that exists between water supply and demand, trade-offs in water allocation amongst different users and policy makers are critical. The objective of this study was to investigate renewable energy choices for SA 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 goods or services. 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 World Business Council for Sustainable Development (WBCSD) Global Water Tool, which helps organizations 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 study has considered 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 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 significant water uses and impacts during pre-generation and generation stages 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 impact 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 production of energy m renewable energy sources in the pre-generation and generation stages. 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 water use impacts associated with non-renewable energy.

## 2.2 Data collection

The assessment included a review of the available literature, focussing on South Africa specific data on water use impacts associated with the various energy types. A review of international literature was undertaken 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 interviewed focused on accessing quantitative data to fill gaps. In many cases the investment in renewable energy generation is still at a very early stage of development and thus data was 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 the generation 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:

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

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

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

Some energy production stages involve several processing options. For example, coal transportation can be through batch (for example 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:

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

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

where $C_{i,L}$ is lower limit of water consumption in the $i^{th}$ stage, and $W_{i,L}$ is lower limit of water withdrawal in the $i^{th}$ stage.

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 report).

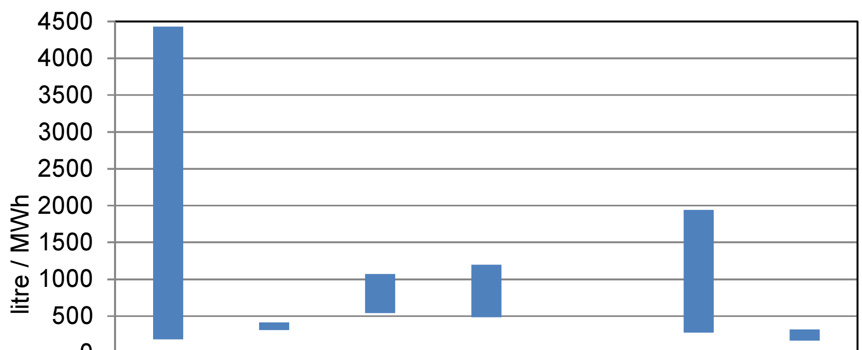
# 3. Findings

## 3.1 Pre-generation water use: international data

### 3.1.1 Water withdrawal (onsite and upstream)

Conventional thermal power plants commonly use coal, nuclear, oil and gas fuels. In these plants, energy production involves various stages including fuel acquisition, processing and transportation. Water is required in coal mining, washing, beneficiation, transportation and power plant construction. Similarly, water use in nuclear power plants is for uranium mining, milling, conversion, enrichment, fuel fabrication, power plant construction and fuel disposal. Extraction, purification, transportation and storage also demand water in the production of energy from natural gas or oil. In this investigation, water usage in the production of energy from renewable energy sources is also considered, and the main renewable energy sources covered are biomass, hydro, solar (PV and CSP) and wind. Biomass can be converted into energy carriers such as biodiesel, methanol, ethanol and hydrogen, with water being required in cultivation of fuel crops. Upstream water withdrawal for growing fuel crops includes water used in the production of farm inputs such as fertilizer. Corn, jatropha, soybean, maize rape seed, sugar beet and switchgrass fuel crops are covered in this investigation. Upstream data for hydroelectric power plants is scarce (Fthenakis & Kim 2010).

Figure 3.1 shows water withdrawals for conventional and renewable energy sources in the pre-generation phase, based on data reported by DoE (1983), Gleick (1994), Inhaber (2010) and Fthenakis and Kim (2010). It should be noted that that there are variations in the values reported by different investigators. Hence, value ranges are used throughout this report.




| | Coal | Nuclear | Natural gas | CSP | Hydro | PV | wind |
|---|---|---|---|---|---|---|---|
| Min | 184 | 312 | 539 | 485 | 1 | 276 | 170 |
| Max | 4428 | 415 | 1071 | 1200 | 1 | 1942 | 320 |

**Figure 3.1: Water withdrawals during the pre-generation phase for the production of energy from conventional and renewable fuels. Biomass is excluded**

***Conventional energy sources***

It is observed that coal-fired thermal power plants withdraw the highest range of water from reservoirs. Transportation of coal in the form of slurry draws the highest amount of water (up to 4 528 litres/MWh) in the pre-generation phase. On the other hand, transportation of coal by train is more water-efficient (26-38 litres/MWh). Water withdrawal during plant construction is relatively low (11-45 litres/MWh). Over the whole pre-generation phase, 184-4428 litres/MWh is withdrawn for various processes until the coal is ready for use by the power plant. For natural gas, a significant amount of water is withdrawn during extraction. Over the entire pre-generation phase, 539-1 071 litres/MWh of water is withdrawn during the production of energy from natural gas. Nuclear power draws the lowest amount of water (amongst conventional fuels) during the pre-generation phase (312-415 litres/MWh).

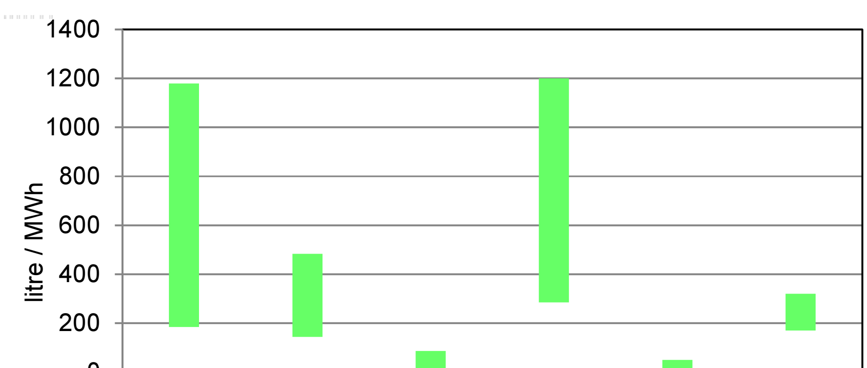
***Renewable energy sources***

Biomass values have been excluded in Figures 3.1 – 3.6 due to their very high ranges – the reader is referred to the tables in the appendix for values related to this fuel source. There is variation in water withdrawals for biomass production depending on the crop and location (weather and other factors). Amongst the crops considered in this investigation, herbaceous perennials exhibit the largest demand for water (435 600 litres/MWh), with hybrid poplar (USA) being the most water-efficient fuel crop (up to 187 litres/MWh, including onsite and upstream water consumption) in the pre-generation phase. Geothermal is also water-intensive (up to 30 000 litres/MWh). The observed water withdrawal levels in PV technology are mostly attributed to material fabrication (upstream) with insignificant water demand onsite. The lowest demand for water in the pre-generation phase is observed in concentrated solar power (CSP). Water withdrawals for wind during pre-generation are mostly attributed to the usage of steel, iron and glass fibre to manufacture wind turbines upstream (Fthenakis & Kim 2010) and to the mining of rare earth minerals. Water withdrawals for hydropower are limited but Inhaber (2004) reported a value of (1.0 litre/MWh).

The intermittent nature of some renewable energy sources, such as solar radiation and wind , is a common reason for governments to prioritize investments in dispatchable energy technologies such as coal, nuclear or gas over renewable energy sources. One way of overcoming this limitation is to back up the renewable energy power plant with a conventional source of energy (Cao & Christensen 2000). This affects the total water requirements in the hybrid renewable energy technologies. Inhaber (2004) investigated water withdrawal factors for hybrid solar and wind technologies and found that 100 000 litres/MWh was required to back up a solar photovoltaic, solar thermal or wind power plant.

### 3.1.2 Water consumption: international data

Figure 3.2 shows water consumption levels for conventional and renewable energy sources in the pre-generation phase, based on the data reported by DoE (1983), Gleick (1994), Inhaber (2010) and Fthenakis and Kim (2010).




| | Coal | Nuclear | Oil/gas | CSP | PV | wind |
|---|---|---|---|---|---|---|
| Min | 184 | 144 | 2 | 285 | 0 | 170 |
| Max | 1179 | 483 | 87 | 1200 | 50 | 320 |

**Figure 3.2: Water consumption during the pre-generation phase for production of energy from conventional and renewable fuels. For wind, estimates of water withdrawals are used for consumption. Biomass is excluded.**

***Conventional energy sources***

It is again observed that coal-fired thermal power plants consume the highest range of water. Transportation of coal in the form of slurry draws the highest amount of water (420 – 870 litres/MWh), while surface mining consumes the least quantity of water (420 – 870 litres/MWh) in the pre-generation phase. Over the entire pre-generation phase, 184 - 1 179 litres/MWh is consumed by various processes until the coal is ready for use by the power plant. Nuclear energy production consumes 144-483 litres/MWh, with natural gas being most water-efficient (2- 87 litres/MWh) amongst the conventional fuels considered in the present work.

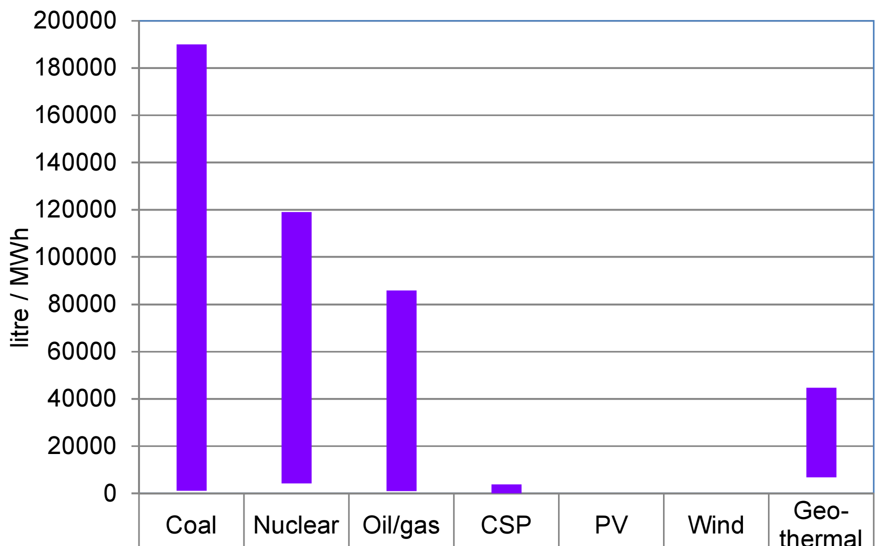
***Renewable energy sources***

For renewable energy, sugar beet consumes the largest amount of water (972 000 litreslitres/MWh), with hybrid poplar (USA) being the most water-efficient fuel crop (up to 187 litreslitres/MWh, including onsite and upstream water consumption) in the pre-generation phase (The reader is referred to the tables in the appendix section). The relatively high levels of water withdrawal observed in wind technology are mostly attributed to upstream processes with insignificant water demand onsite. The lowest consumption of water in the pre-generation phase is observed in solar PV plants with wind energy consuming intermediate levels of water during pre-generation. Data are not available on water consumption in the pre-generation phase of hydro power.

## 3.2 Generation water use: international data

### 3.2.1 Water withdrawal

Figure 3.3 shows water withdrawal levels for conventional and renewable energy sources in the generation phase, based on data reported by DoE (1983), Gleick (1994), Inhaber (2010) and Fthenakis and Kim (2010).




| | Coal | Nuclear | Oil/gas | CSP | PV | Wind | Geo-thermal |
|---|---|---|---|---|---|---|---|
| Min | 1100 | 4200 | 950 | 15 | 0 | 0 | 6800 |
| Max | 190000 | 119000 | 85900 | 3800 | 15 | 4 | 44700 |

**Figure 3.3: Water withdrawal during the generation phase of energy from conventional and renewable fuels. Biomass and hydro are excluded.**

***Conventional energy sources***

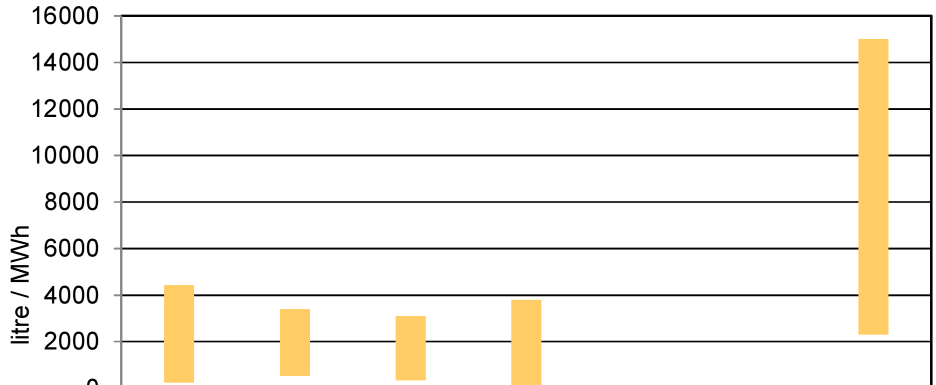
It is seen that coal-fired thermal power plants withdraw the highest range of water from reservoirs. The once-through method is the most water-inefficient technique of wet cooling (up to 190 000 litres/MWh) in the generation phase. On the other hand, the use of a cooling pond withdraws the least amount of water (1 100-2 300 litres/MWh). Over the whole generation phase, 1 100-190 000 litres/MWh is withdrawn for various processes within the power plant. The integrated gasification combined cycle (IGCC) draws the lowest amount of water (amongst conventional fuels) during the generation phase (855-3 100 litres/MWh), with nuclear power exhibiting an intermediate range.

***Renewable energy sources***

For renewable energy, hydro energy by its nature withdraws the largest amount of water (up to 791 677 litres/MWh - not included in Figure 3.3 for scale reasons), with PV and wind being the most water-efficient in the generation phase. This observation is consistent with findings of Fthenakis and Kim (2010).

### 3.2.2 Water consumption

Figure 3.4 shows water consumption levels for conventional and renewable energy sources in the generation phase, based on the data reported by DoE (1983), Gleick (1994), Inhaber (2010) and Fthenakis and Kim (2010).




| | Coal | Nuclear | Oil/gas steam | CSP | PV | Wind | Geo-thermal |
|---|---|---|---|---|---|---|---|
| Min | 242 | 530 | 341 | 15 | 0 | 0 | 2300 |
| Max | 4430 | 3400 | 3100 | 3800 | 15 | 4 | 15000 |

**Figure 3.4: Water consumption during the generation phase of energy from conventional and renewable fuels. For wind the values of consumption were estimates from withdrawals. Biomass and hydro are excluded.**

***Conventional energy sources***

Coal-fired thermal power plants consume the highest amount of water. The subcritical wet-tower method of wet cooling consumes the highest amount of water (up to 4 430 litres/MWh) in the generation phase. On the other hand, the use of a supercritical cooling pond consumes the least amount of water (242 litres/MWh). Over the whole generation phase, 242-4 430 litres/MWh is consumed during various processes within the power plant.

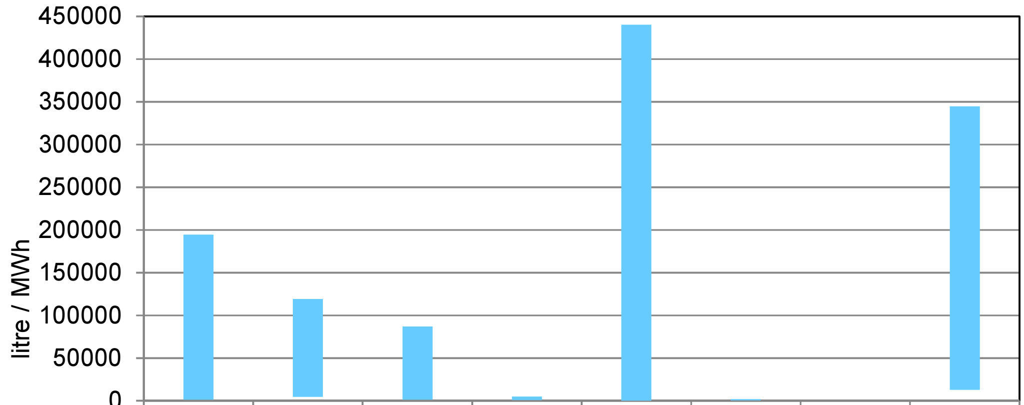
***Renewable energy sources***

Hydro energy consumes the largest amount of water (up to 210 000 litres/MWh), with PV and wind being the most water-efficient in the generation phase. This observation is again consistent with findings of Fthenakis and Kim (2010).

## 3.3 Water use over the lifecycle: international data

### 3.3.1 Water withdrawal

Water withdrawal levels over the lifecycle of conventional and renewable energy sources are presented in Figure 3.5.




| | Coal | Nuclear | Oil/ gas steam | CSP | Hydro | PV | Wind | Geo-thermal |
|---|---|---|---|---|---|---|---|---|
| Min | 1284 | 4512 | 1489 | 500 | 80 | 276 | 170 | 12800 |
| Max | 194428 | 119415 | 86971 | 5000 | 440000 | 1957 | 324 | 344700 |

**Figure 3.5: Water withdrawal over the life cycle of energy production from conventional and renewable fuels. Biomass is excluded.**

***Conventional energy sources***

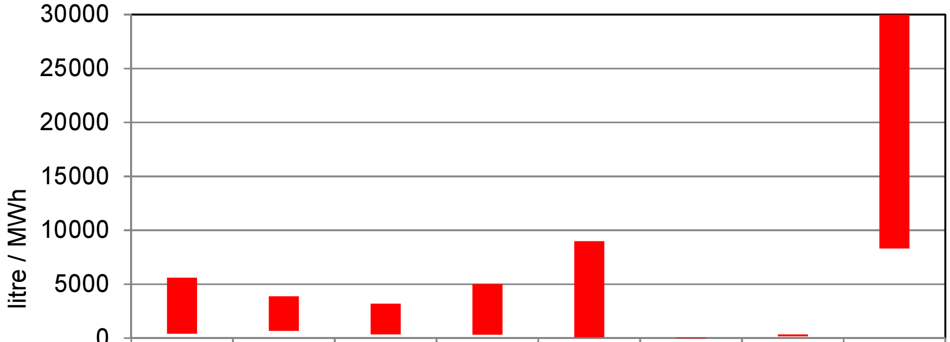
Coal-fired thermal power plants withdraw the highest amount of water (1 284-194 428 litres/MWh) from reservoirs. The high water withdrawal is attributed predominantly to cooling during power generation. On the other hand, oil/gas exhibits the lowest range of water intensity (1 489-86 971litres/MWh), with nuclear energy being intermediate.

***Renewable energy sources***

Hydro energy draws the largest amount of water (up to 440 000 litres/MWh), with PV and wind being the most water-efficient over the considered stage of the lifecycle. It should be noted that the hydro range is broad, and the high value is reflective of one estimate. Other estimates are considerably lower. These observations are consistent with findings of Fthenakis & Kim (2010) and Wassung (2010).

### 3.3.2 Water consumption

The variation of water consumption across different fuels over the lifecycle is shown in Figure 3.6.




| | Coal | Nuclear | Oil/ gas steam | CSP | Hydro | PV | Wind | Geo-thermal |
|---|---|---|---|---|---|---|---|---|
| Min | 426 | 674 | 343 | 300 | 80 | 0 | 170 | 8300 |
| Max | 5609 | 3883 | 3187 | 5000 | 9000 | 65 | 324 | 30000 |

**Figure 3.6: Water consumption over the life cycle of energy production from conventional and renewable fuels. Biomass is excluded.**

***Conventional energy sources***

For conventional fuels, coal-fired thermal power plants consume the highest amount of water. Most of the water is consumed during generation, probably through evaporation. Amongst conventional fuels, oil and gas are more favourable from a water perspective.

***Renewable energy sources***

For renewable energy, geothermal power consumes the largest amount of water (up to 30 000 litres/MWh), attributed to production of a large volume of waste water (Inhaber 2004). PV and wind are the most water-efficient over the considered stages of the lifecycle. This observation is consistent with findings of Fthenakis and Kim (2010) and Wassung (2010). It should also be noted that hydro power is relatively less water-efficient compared to conventional fuels due to evaporative water loss. Evaporation takes place at the boundary between the water surface and air layer. So, for a given rate of evaporation (per unit area), the volumetric water loss increases with the exposed surface area of the water. A dam raises the surface area of the water exposed to the ambient environment, thereby augmenting the bulk amount of water that leaves the surface in form of vapour.

## 3.4 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 this country. However, disaggregated data on water withdrawal and consumption at specific stages of energy generation is scarce across fuels. In general, 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 3.1. 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).

**Table 3.1: 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 | 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.

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. Fthenakis and Kim (2010) reported a water withdrawal value of 120 000 litres/MWh for a nuclear power plant using the once-through cooling method, which is comparable with the value for the Koeberg power plant. 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. Table 3.2 shows water requirements for biofuel production.

**Table 3.2: Water withdrawal requirements for biomass energy**

*Source: Gerbens-Leenes et al. (2008)*

| Sugar cane | Heat from biomass | Water use litre/MWh |
|---|---|---|
| **Potato** | Heat from biomass | 108 000 |
| **Sorghum** | Heat from biomass | 176 400 |
| **Sugar Cane** | Electricity from biomass | 176 400 |
| **Maize** | Electricity from biomass | 151 200 |
| **Potato** | Electricity from biomass | 183 600 |
| **Sorghum** | Electricity from biomass | 295 200 |
| **Sugar Cane** | Bio-ethanol from biomass | 352 800 |
| **Maize** | Bio-ethanol from biomass | 334 800 |
| **Potato** | Bio-ethanol from biomass | 183 600 |
| **Sorghum** | Bio-ethanol from biomass | 684 000 |

Sorghum requires the highest amount of water (684 000 litres/MWh), with potato having the lowest water intensity (108 000 litres/MWh). Maize is a food crop, which consequently creates competition between food and fuel for the same resource (here maize is part of the water energy food security nexus). Stone *et al.* (2010) also found that production of bioethanol from grain and grain sorghum consumes the highest quantity of water compared to other feedstock (as discussed earlier).

Data on usage of water in the production of energy from CSP and PV is scarce. Olivier (2013) reported water consumption of 767 000 litres during the construction phase of a 4.5 MW hydro power plant. For wind, Hagemann (2013) reported water usage of 817 000 litres in the construction phase of a 120MW power plant. The plant would use 3 650 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 below 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, for comparative purposes and in decision-making between renewable and conventional fuel choices. However, the focus of the broader project is on renewable energy and its water footprint. This discussion covers water and water impact for each fuel.

# 4. Analysis

## 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, which indicates that more attention needs to be paid to this stage of energy production. However, disaggregated data on water usage (stage-by-stage withdrawal and consumption levels) for South Africa is scarce. In view of this, water usage patterns from other countries can be used as indicators 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 but 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 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 dry-cooling systems 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 2013a). Specific withdrawals are not disclosed by Synfuels operations in South Africa (only withdrawals associated with global operations is 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 2013a).

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 a specific location.

## 4.3 Carbon capture and storage (CCS)

A power plant with a CCS technology requires more fuel to produce the same amount of energy than a conventional power plant. 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 plants (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 three systems differ due to their application. The primary water loop is a closed system with pressurized water. It transfers heat from the reactor vessel to the secondary system through a heat exchanger. Cool water is returned to the reactor vessel with no water consumption in this loop. Steam is produced in the secondary loop, and used to drive a turbine which generates electricity. After flowing through the turbine, the steam is condensed and returned to the steam generator unit. The tertiary loop uses seawater to condense the steam (Eskom 2013a).

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 ambient environment or to a heat recovery system.

The Koeberg Nuclear Power Station is built adjacent to an abundant water source (the ocean) and hence uses the once-through cooling method in the tertiary loop to condense the steam after driving the turbine. The cooling water is circulated back into the ocean at an elevated temperature. Water consumption is marginal, with a small proportion of 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 in to 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 the contamination of ground water (Kharaka *et al.* 2013). In this regard, some of the contaminants include methane, benzene and gasoline and the diesel range of 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 about water usage and hydraulic fracturing in the Karoo area. It has been estimated that 20-25 million litres of water may be required to drill one well (Fig, 2013). 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 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 cooling is an option for areas where water is a constraint, but this method of cooling is less efficient than wet cooling. Compared to 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. Sinha *et al.* (2013) found 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, which is aimed at removing dust from the panels to maintain a high level of the transmission of solar radiation. International literature suggests values of 15 litres/MWh for CPV and PV (NREL 2002; Fthenakis & Kim 2010). Information is scarce on the frequency of PV-panel cleaning in South Africa. It is likely to depend, in part, on the environment where the system is installed. Frequent cleaning is required in dusty conditions, but the impact of concentrated photovoltaic (CPV) and photovoltaic (PV) on water is negligible.

## 4.7 Wind power

Wind power does not use water in the acquisition or supply of the fuel per se. It does, however, use water in the acquisition and processing 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 cell phones, tablets, 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 of the turbine blades from time to time.

A wind power plant with a total capacity of 8.4 MW, requires 1400 tons of rare earth elements (Martin & Fischer 2012). Every ton of rare earth mineral produced uses 75 $m^3$ acidic wastewater and one ton of radioactive waste residue (which contains water) (Hurst 2010). Wastewater from rare earth mining in China is often discharged without appropriate treatment, impacting on potable water. The water use in the production of rare earth elements such as neomycin do 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 in-stream water use. 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). Pegram and others (2011) summarise the pertinent points of this paper as relevant to hydropower, to which the reader is referred. Important considerations are evaporation and seepage. 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 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) estimate 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) indicate 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: 2020) 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 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 $21 m^3$/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). 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. Conclusions and recommendations

## 5.1 Conclusions

Water usage in the production of energy from conventional and renewable fuels has been explored in this study. 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. Results show that there are 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 over the life-cycle of energy production, especially for thermoelectric power plants operated with wet-cooling systems. 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 in terms of withdrawal (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. In this case the water consumption could be disregarded altogether. 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.

## 5.2 Recommendations

a) From a water perspective, solar PV and wind should be promoted in South Africa. Moreover, these energy sources are low-carbon.

b) It is necessary to consider all the stages in the energy cycle for meaningful comparison of water usage across different fuels. This would enable targeted interventions aimed at reducing negative impacts on water resources.

c) There is the need for taking systematic data on water usage over the life cycle of all major conventional and renewable energy sources in South Africa.

d) 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 Aquila CPV plant in Touws River would also be worthwhile considering.

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# Appendix: Data on international water usage in energy production.

**Table A1: Pre-generation water withdrawals for thermoelectric fuel cycles.**

| Fuel | Energy production stage | On-site litre/MWh | Upstream litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| **Coal** | Eastern underground mining & washing | 190 | 507 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Eastern surface mining (0.9 seam thickness ) | 38[a] | 148 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Western surface mining (0.7m seam thickness) | NA | 11 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | US coal mining | 106 | 53 | USA | Gleick 1993 Fthenakis & Kim 2010 |
| | Beneficiation (Material fractionation) | >45 | 53 | USA | Fthenakis & Kim 2010 |
| | Transportation (train) | NA | 26 - 38 | USA | Fthenakis & Kim 2010 |
| | Transportation (slurry pipeline) | 450 | 3100 | USA | Fthenakis & Kim 2010 |
| | Construction – coal-power plant | NA | 11-45 | USA | Fthenakis & Kim 2010 |
| | | | | | |
| **Nuclear** | Uranium mining | 38 | 15 | USA | Fthenakis & Kim 2010 |
| | Milling | 19 | 68 | USA | Fthenakis & Kim 2010 |
| | Conversion | 15 | 8 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Enrichment (diffusion) | 79 | 115 | USA | Fthenakis & Kim 2010 |
| | Enrichment (centrifuge) | 8 | 102 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Fuel fabrication | 0.3 | 0.4 | USA | DOE 1983, Fthenakis & Kim (2010) |
| | Power plant construction (PWR) | NA | 19 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Power plant construction ( BWR) | NA | 38 | USA | DOE (1983), Fthenakis & Kim (2010) |
| | Spent fuel disposal | NA | 19 | USA | Kim & Fthenakis 2005 Fthenakis & Kim 2010 |
| | | | | | |
| **Natural gas** | Extraction (onshore) | 130 | 300 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Extraction (offshore) | 0.8 | 0.4 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Purification | 64 | NA | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Pipeline transportation | 1.5 | 38 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Storage (underground) | NA | 15 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Power plant environmental control | NA | 89 | USA | Fthenakis & Kim 2010 |

[a] Washing only.

BWR- Boiling water reactor, NA- Not applicable, PWR- Pressurized water reactor.

**Table A2: Pre-generation water consumption for thermoelectric fuel cycles in the United States (Upstream water consumption not included).**

| Fuel type | Energy production stage | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|
| **Coal** | Surface mining | 11– 53 | USA | Fthenakis & Kim 2010 |
| | Underground mining | 30–200 | USA | Fthenakis & Kim 2010 |
| | Washing | 30–64 | USA | NETL 2006 , Fthenakis & Kim 2010 |
| | Beneficiation | 42–45 | USA | Fthenakis & Kim 2010 |
| | Transportation – slurry pipeline | 420–870 | USA | DOE 1983, Fthenakis & Kim 2010 |
| **Nuclear** | Surface uranium mining | 200 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Underground uranium mining | 4 | USA | Fthenakis & Kim 2010 |
| | Milling | 83–100 | USA | Fthenakis & Kim 2010 |
| | Conversion | 42 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Enrichment (diffusion) | 45–130 | USA | Fthenakis & Kim 2010 |
| | Enrichment (centrifuge) | 4–19 | USA | Fthenakis & Kim 2010 |
| | Fabrication | 11 | USA | Fthenakis & Kim 2010 |
| **Natural gas** | Extraction (onshore) | NG | USA | Gleick 1993. Fthenakis & Kim 2010 |
| | Extraction (offshore) | NG | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Purification | 57 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Pipeline transportation | 30 | USA | Gleick 1993 Fthenakis & Kim 2010 |

**Table A3: Pre-generation water withdrawal factors of PV and wind technologies for manufacturing the devices and constructing the power plants.**

| Technology/ fuel | Type | On-site | Upstream litre/MWh | Reference |
|---|---|---|---|---|
| **PV** | Multi-Si | 200 | 1 470 | Fthenakis and Kim 2010 |
| | Mono-Si | 190 | 1 530 | Fthenakis and Kim 2010 |
| | Frame | NA | 64 | Fthenakis and Kim 2010 |
| | CdTe | 0.8 | 575 | Fthenakis and Kim 2010 |
| | BOS | 1.5 | 210 | Fthenakis and Kim 2010 |
| **Solar thermal** | | | 4-5 | Inhaber 2010 |
| **Wind** | Off shore, Denmark (CF=29%) | | 230 | Schleisner 2000 Fthenakis and Kim 2010 |
| | Off shore, Denmark (CF=46%) | | 170 | Schleisner L.2000, Fthenakis and Kim 2010 |
| | On land, Denmark (CF=25%) | | 170 | Fthenakis and Kim 2010 |
| | Onshore, Denmark (CF=32%) | | 320 | Fthenakis and Kim 2010 |
| | On land, Italy (CF=19%) | | 250 | Fthenakis and Kim 2010 |
| | On shore, Spain (CF=23%) | | 210 | Fthenakis and Kim 2010 |

CF-capacity factor, BOS- balance of systems

**Table A4: Pre-generation water withdrawal factors for biomass/bioenergy production**

| Biomass | Energy type | On-site litre/MWh | Upstream litre/MWh | Reference |
|---|---|---|---|---|
| **Hybrid Poplar, USA** | Electricity | 0 | 187 | Mann & Spath 1997 |
| **Herbaceous perennials, Southwestern USA, irrigation** | Electricity | 435 600 | 1,116 | Klass 1998, Fthenakis & Kim 2010 |
| **Corn, USA** | Ethanol | 1 260-43 560 | NA | Wu et al. 2009 |
| **Switchgrass, USA** | Ethanol | 180-936 | NA | Wu et al 2009 |
| **Corn, Illinois** | Ethanol | 1 818 | NA | Mubako & Lant 2008 |
| **Corn, Iowa** | Ethanol | 612 | NA | Mubako & Lant 2008 |
| **Corn, Nebraska** | Ethanol | 67 320 | NA | Mubako & Lant 2008 |

**Table A5: Pre-generation water consumption factors for biomass/bioenergy production**

| Biomass | Energy type | On-site litre/MWh | Upstream litre/MWh | Reference |
|---|---|---|---|---|
| **Hybrid Poplar, USA** | Electricity | 0 | 187 | Mann & Spath 1997 |
| **Maize, global average** | Electricity | 72 000 | NA | Gerbens-Leenes et al 2009 |
| **Sugar beet, global average** | Electricity | 972 000 | NA | Gerbens-Leenes et al 2009 |
| **Soybean, global average** | Electricity | 342 000 | NA | Gerbens-Leenes et al 2009 |
| **Jatropha, global average** | Electricity | 831 600 | NA | Gerbens-Leenes et al 2009 |
| **Corn, USA** | Ethanol | 972-30 960 | NA | Wu et al 2009 |
| **Corn, USA** | Ethanol | 648-204 480 | NA | Chiu et al. 2009 |
| **Switchgrass, USA** | Ethanol | 180-936 | NA | Wu et al 2009 |
| **Sugar beet, global average** | Ethanol | 126 000 | NA | Gerbens-Leenes et al 2009 |
| **Soybean, global average** | Biodiesel | 781 200 | NA | Gerbens-Leenes et al 2009 |
| **Rapeseed, global average** | Biodiesel | 882 000 | NA | Gerbens-Leenes et al 2009 |

**Table A7: Generation water withdrawal and consumption for thermoelectric fuel cycles**

| Power plant | Energy production stage | Withdrawal litre/MWh | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| **Coal** | Once-through, subcritical | 103 000 | 530 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Once-through, supercritical | 85 600 | 450 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Once-through | 76 000 -190 000 | 1 140 | USA | Najjar et al. 1979, Fthenakis & Kim 2010 |
| | Once-through | NA | 1 210 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Once-through (fluidized-bed) | NA | 950 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Cooling pond, subcritical | 67 800 | 3 030 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Cooling pond, | 57 200 | 242 | USA | NETL 2009, Fthenakis & |

| Power plant | Energy production stage | Withdrawal litre/MWh | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| | supercritical | | | | Kim 2010 |
| | Cooling pond | 1 100–2 300 | 1 000–1 900 | USA | Najjar et al. 1979, Fthenakis & Kim 2010 |
| | Wet tower, subcritical | 2 010 | 1 740 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower, subcritical | 2 590 | 2 560 | USA | NETL 2007, Fthenakis & Kim 2010 |
| | Wet tower, subcritical | 4 430 | 4 430 | USA | Fthenakis & Kim 2010 |
| | Wet tower, supercritical | 2 500 | 1 970 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower, supercritical | 3 940 | 3 940 | USA | Fthenakis & Kim 2010 |
| | Wet tower, supercritical | 2 270 | 2 240 | USA | NETL 2007, Fthenakis & Kim 2010 |
| | Wet tower | 1 900–2 300 | 1 700–1 900 | USA | Najjar et al 1979, Fthenakis & Kim 2010 |
| | Wet tower | NA | 3 100 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Wet tower, eastern | NA | 2 800 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Wet tower, western | NA | 1900 | USA | DOE 1983, Fthenakis & Kim 2010 |
| **Nuclear** | Once-through | 119 000 | 530 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Once-through | 95 000 –230 000 | 1500 | USA | Najjar et al. 1979, Fthenakis & Kim 2010 |
| | Cooling pond | 1 900–4 200 | 1 700–3 400 | USA | Najjar et al 1979, Fthenakis & Kim 2010 |
| | Wet tower | 4 200 | 2 300 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | 3 000–4 200 | 2 800–3 400 | USA | Najjar et al. 1979, Fthenakis & Kim 2010 |
| | Wet tower (LWR) | NA | 3 200 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Wet tower (HTGR) | NA | 2 200 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| **Nuclear** | Wet tower (PWR) | NA | 3 100 | USA | Fthenakis & Kim 2010 |
| | Wet tower (BWR) | NA | 3 400 | USA | DOE 1983, Fthenakis & Kim 2010 |
| **Oil/ gas steam** | Once-through | 85 900 | 341 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Once-through | NA | 1 100 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Once-through | NA | 950 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Cooling pond | 29 900 | 420 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | 950 | 610 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | NA | 3 100 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | Wet tower (oil) | NA | 1 100 | USA | DOE 1983, Fthenakis & |

| Power plant | Energy production stage | Withdrawal litre/MWh | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| | | | | | Kim 2010 |
| **NGCC** | Once-through | 34 100 | 76 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Once-through | 28 000–76 000 | 380 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Cooling pond | 22 500 | 910 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | 568 | 490 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | 1 030 | 1 020 | USA | NETL 2007, Fthenakis & Kim 2010 |
| | Wet tower | 1 900 | 1 900 | USA | Fthenakis & Kim 2010 |
| | Wet tower | 870 | 680 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Dry cooling | 15 | 15 | USA | NETL 2009, Fthenakis & Kim 2010 |
| **IGCC** | Wet tower | 855 | 655 | USA | NETL 2009, Fthenakis & Kim 2010 |
| | Wet tower | 1 420–1 760 | 1 360–1 420 | USA | NETL 2007, Fthenakis & Kim 2010 |
| | Wet tower | 2 600–3 100 | 2 570–3 140 | USA | Fthenakis & Kim 2010 |
| | Wet tower | 950 | 680 | USA | Gleick 1993, Fthenakis & Kim 2010 |

NGCC- natural gas combined cycle, IGCC- integrated gasification combined cycle, LWR- light water reactor, HTGR- high temperature gas-cooled reactor, PWR- pressurized water reactor, BWR- boiling water reactor.

**Table A8: Water use in renewable power plants.**

| Power plant | Type | Withdrawal litre/MWh | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| **Biomass** | Steam plant | 1 800 | 1 800 | USA | Berndes 2002 |
| | Biogas-steam, wet cooling | 2 100 | 1 700 | USA | Berndes 2002 |
| | Biogas-steam, dry cooling | 150 | 0 | USA | Berndes 2002 |
| | | | | | |
| **CPV** | CPV | 0 | 0 | USA | Fthenakis & Kim 2010 |
| | CPV, cleaning | 15 | 15 | USA | NREL 2002, Fthenakis & Kim 2010 |
| **CSP** | Tower | 2 900 | 2 900 | USA | NREL 2002, Fthenakis & Kim 2010 |
| | Tower | 3 200 | 3 200 | USA | NREL1997, Fthenakis & Kim 2010 |
| | Tower, wet cooling | 3 100 | 3 100 | USA | NREL 2003, Fthenakis & Kim 2010 |
| | Parabolic trough, wet cooling | 3,700 | 3,700 | USA | NREL 2006, Fthenakis & Kim 2010 |
| | Parabolic trough, dry cooling | 300 | 300 | USA | NREL 2006, Fthenakis & Kim 2010 |
| | Parabolic trough, wet cooling | 3 100 | 3 100 | USA | NREL 2003, Fthenakis & Kim 2010 |
| | Parabolic trough, wet | 3 100–3 800 | 3 100–3 800 | USA | Cohen et al. 1999, |

| Power plant | Type | Withdrawal litre/MWh | Consumption litre/MWh | Country | Reference |
|---|---|---|---|---|---|
| | cooling | | | | Fthenakis & Kim 2010 |
| | Trough | 2 100 | 2 100 | USA | NREL1997, Fthenakis & Kim 2010 |
| | Dish stirling, cleaning | 15 | 15 | USA | NREL 2002, Fthenakis & Kim 2010 |
| | | | | | |
| **Geothermal** | Dry system | 7 570 | 5 300 | USA | DOE 2006, Fthenakis & Kim 2010 |
| | Dry system | 6 800 | 6 800 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Hot water system | 15 000 | 15 000 | USA | Gleick 1993, Fthenakis & Kim 2010 |
| | Hot water system | 44 700 | 2 300–6 800 | USA | EPRI 1997, Fthenakis & Kim 2010 |
| **Hydro** | | 0 | 17 000 | USA | DOE 1983, Fthenakis & Kim 2010 |
| | | 0 | 38–210 000 | USA | Fthenakis & Kim 2010 |
| | | | 5 300 | USA | Fthenakis & Kim 2010 |
| | | 791 677 | 20 000 | Spain | Carrilo & Frei 2009 |
| **PV** | PV | 0 | 0 | USA | Fthenakis & Kim 2010 |
| | PV, cleaning | 15 | 15 | USA | NREL 2002, Fthenakis & Kim 2010 |
| | | | 1-5 | | Macknick et al. 2012 |
| **Wind** | | 0 | 0 | USA | DOE 2006, Fthenakis & Kim 2010 |
| | | 4 | 4 | USA | Fthenakis & Kim 2010 |

**Table A9: Water withdrawals and consumption over lifecycle of fuels in USA and China**

| Fuel type | Withdrwal litre/MWh | Consumption litre/MWh | Reference |
|---|---|---|---|
| **Coal, re-circulating** | 2 500 | | Fthenakis & Kim 2010 |
| **Coal, once-through** | 98 400 | | Fthenakis & Kim 2010 |
| **Coal, cooling pond** | 65 300 | | Fthenakis & Kim 2010 |
| **Coal** | 16,052 | 692 | Wilson et al. 2012 |
| **Geothermal** | 700 | 700 | Wilson et al. 2012 |
| **Nuclear, re-circulating** | 5 000 | | Fthenakis & Kim 2010 |
| **Nuclear, once-through** | 120 000 | | Fthenakis & Kim 2010 |
| **Nuclear, cooling pond** | 3 900 | | Fthenakis & Kim 2010 |
| **Nuclear** | 14 811 | 572 | Wilson et al. 2012 |
| **Oil/gas re-circulating** | 2 300 | | Fthenakis & Kim 2010 |
| **Oil/gas, once-through** | 85 900 | | Fthenakis & Kim 2010 |
| **Oil/gas, cooling pond** | 29 900 | | Fthenakis & Kim 2010 |
| **Natural gas** | 6 484 | 172 | Wilson et al. 2012 |
| **PV, multi-Si** | 1 900 | | Fthenakis & Kim 2010 |
| **PV, CdTe** | 800 | | Fthenakis & Kim 2010 |
| **PV** | 231 | 2 | Wilson et al. 2012 |
| **Solar thermal** | 800 | 800 | Wilson et al. 2012 |
| **Wind** | <61 | <1 | Wilson et al. 2012 |
| **Wind** | 640 | | Li et al. 2012 |
| **Hydro** | 80 | | Fthenakis & Kim 2010 |
| **Hydro** | 440 000 | 9,000 | Wilson et al. 2012 |
| **Biomass, South west** | 438 000 | | Fthenakis & Kim 2010 |
| **Biomass, Midwest** | 2 000 | | Fthenakis & Kim 2010 |