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HOMER analysis of the water and renewable energy nexus for water-stressed urban areas in Sub-Saharan Africa

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ABSTRACT

Climate change, population growth and rapidly increasing urbanisation severely threaten water quantity and quality in Sub-Saharan Africa. Treating wastewater is necessary to preserve the water bodies; reusing treated wastewater appears a viable option that could help to address future water challenges. In areas already suffering energy poverty, the main barrier to wastewater treatment is the high electricity demand of most facilities. This work aims to assess the benefits of integrating renewable energy technologies to satisfy the energy needs of a wastewater treatment facility based on a conventional activated sludge system, and also considers the case of including a membrane bioreactor so treated wastewater can be reused for irrigation. Using HOMER, a software tool specifically developed for optimal analysis of hybrid micro-generation systems, we identify the optimal combination of renewable energy technologies for these facilities when located in a specific water-stressed area of Sub-Saharan Africa and assess whether the solutions are cost-effective. The analysis shows investment in renewable technologies is cost-effective when the true cost of electricity or average days of power outages per year are considered. Integration of photovoltaic panels, a wind turbine and internal combustion engine fuelled by biogas produced by anaerobic digestion can cover between 33% and 55% of the electricity demand of the basic wastewater facility, at a levelised cost of energy lower than the true cost of electricity. In the case of water reuse, the techno-economically viable solutions identified by HOMER can cover 13% of energy needs. Finally, we discuss how the proposed solutions could provide a large contribution to socio-political security, in both domestic and cross-border contexts.

1. Introduction

The most significant challenges currently faced by Sub-Saharan Africa arise from or intersect with water issues (Freitas, 2013). According to the World Health Organization, over 40% of the population in Sub-Saharan Africa do not have access to safe drinking water. Water is not only scarce, but also of poor quality; 45% of the population only have access to shared and inadequate sanitation facilities. Indeed, 30% of people only gained access to improved sanitation in recent years, and Sub-Saharan Africa missed the 2015 Millennium Development Goal sanitation target: "halve the proportion of the population without sustainable access to basic sanitation" (Unicef, 2015). Moreover, climate change, the growing population and increasing urbanisation act as stress multipliers. Assessment Report 5 of the Intergovernmental Panel of Climate Change (IPCC, 2014) provides a clear picture of the effects of climate change: the medium-risk scenario predicts an increase in the land temperature of most regions of Africa of more than 2 °C, particularly in arid regions. Climate change will reduce water availability, increase hydro-climatic variability in both space and time and raise the risk of extreme weather events. A reduction in precipitation combined with increased temperatures is likely reduce crop production and threaten food security over the long-term, especially as Sub-Saharan Africa mainly relies on rain-fed agriculture.

A recent report by Hove et al. (2013) predicted the population of Sub-Saharan Africa will almost double by 2050. Since the early 1970s, Sub-Saharan Africa has experienced the highest rate of urban population growth worldwide, averaging up to 5% per year (Todaro and Smith, 2012). According to Nyenje et al. (2010), monitoring reports indicate the populations of the mega-cities in Sub-Saharan Africa are rapidly increasing, and therefore, so is the

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Nomenclature

C	cost *($)*
CHP	combined heat and power
COD	chemical oxygen demand
COE	cost of energy *($/kWh)*
CRF	capital recovery factor
E	Energy *(kWh)*
i	real interest rate
ICE	internal combustion engine
N	number of year
NPC	net present cost
PE	population equivalent
PV	photovoltaic
R	Lifetime *(year)*
SS	suspended solid *(kg/person/year)*

Subscripts

ann,tot	total annualized
def	deferrable loads
el	electrical
grid, sales	sold to the grid
proj	project

total amount of wastewater produced. Less than 30% of wastewater is treated in sewage treatment plants, while the remainder is disposed of via onsite sanitation systems and eventually discharged into groundwater. The total amount of wastewater produced in Sub-Saharan African megacities can be as high as 10–50% of the total precipitation entering these urban areas, which is considerable since precipitation is the most important - if not only – wastewater diluting agent. Recent literature has highlighted the increasing levels of pollution in African water bodies (Ali et al., 2011; Scheren et al., 2000), illustrating the severe impact of effluents on downstream water. Therefore, it is imperative to treat wastewater before discharging it into the drainage basin, and if combined with water reuse, wastewater treatment may provide a solution to satisfy the increasing water demands of Sub-Saharan Africa. Numerous scientists and policy makers (Theregowda et al., 2016) are exploring the wastewater treatment issue and also consider the reuse of treated wastewater as a viable, interesting option. Energy requirements are a major barrier to the implementation of wastewater treatment and reuse strategies: this is a timely topic that urgently needs to be addressed by the energy sector. For the first time, the 2016 World Energy Outlook will explore the energy needs of the global water industry, including wastewater treatment facilities (IEA, 2015).

Sub-Saharan Africa is the most electricity-poor region in the world; according to the 2015 World Energy Outlook access database (WEO, 2016), the average electrification rate is 35%, with urban and rural electrification rates of 59% and 17%, respectively. In this context, it would be difficult to meet the additional demands for energy arising from wastewater treatment facilities. Renewable energy technologies, and in particular micro-grids, represent a possible solution. According to the recent World Bank Energy Report (The World Bank, 2015), Sub-Saharan Africa could increase its current energy capacity by up to 170 GW through the introduction of small installations, such as combined heat-and-power systems and production of biofuels.

The present work investigates the energy needs of wastewater treatment and reclaimed water reuse facilities. We aimed to assess the benefits of integrating renewable energy technologies into wastewater treatment facilities situated in urban areas of water-stressed river basins. In particular, we identify the optimal combinations of renewable energy technologies for a wastewater treatment facility without or with water reuse capacity situated in a given urban area of Sub-Saharan Africa under three different scenarios, and analyse whether the solutions are cost-effective. The work assumes a number of served inhabitants of 10,000 (equal to about 11,000 Population Equivalent, PE). Although a decentralised wastewater treatment facility typically serves from 1,000 to 10,000 PE (Libralato et al., 2012), the authors agree with Gikas and Tchobanoglous (2009) about the difficulty of attributing a precise threshold. Here, we embrace the main concept of decentralised systems, in that the raw wastewater is treated next to the source, in line with the concept of decentralised energy production, next to the user. For the present work, the decentralised facility could even be thought of as being in parallel to the central system, just as the energy production from renewable sources occurs in parallel to the main electricity grid. The urban area is assumed to have a wastewater collection system (which is not always the case), either through pipes or tanks. For water reuse applications, the standard requirements vary according to the specific reuse of the treated water. The present paper focuses on the reuse of water for agricultural irrigation, which is of particular interest since more than 70% of the freshwater used worldwide is used for agricultural irrigation (Capra and Scicolone, 2007; Lazarova et al., 2012). The paper assesses the proposed integrated solutions from a techno-economic point of view using HOMER, a software tool specifically developed for optimal analysis of hybrid micro-generation systems (Lambert et al., 2006).

The exploration of the results is followed by a post-HOMER analysis of how the proposed solution can address security problems and help to mitigate cross-border conflicts. Any initiatives that reduce water pollution and address the problem of water scarcity could act as a conflict relief, given that 75% of the water resources in Sub-Saharan Africa are concentrated in eight major transboundary river basins. Therefore, any usage of cross-boundary water, including that to satisfy increasing energy demand, can represent a potential source of conflict between the states through which these rivers flow (Chellaney, 2011). The Nile river basin, which extends over 11 countries, provides a meaningful example of such cross-border security issues. Upstream countries such as Ethiopia are less industrialised, yet in recent years their needs for water and energy, the latter of which is mainly produced by hydroelectric plants, have increased. Downstream countries, such as Egypt, have also faced increased water and energy demands due to growth of both the population and energy intensive industry, creation of desalination plants and changes in lifestyle (Sowers, 2014). Therefore, any water and energy issues that involve the use of this shared water body can rapidly create tensions, as demonstrated by the construction of a new dam on the river Nile in Ethiopia, the Grand Renaissance Dam, which could threaten the water supply of downstream countries.

In section 2 of this paper, we discuss the wastewater and renewable energy nexus; section 3 describes the methods adopted for the HOMER analysis; section 4 details the system modelled; and section 5 discusses the solutions generated by the simulation. Finally, through a post-HOMER analysis, section 6 addresses the relevance of the proposed technical solutions in the context of the security background of the region.

2. Wastewater and energy nexus

This section provides an overview of the interactions between wastewater and energy, with the aim of clarifying this nexus and