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HOMER analysis of the water and renewable energy nexus for water-stressed urban areas in Sub-Saharan Africa[1]

Caterina Brandoni[a*], Branko Bošnjaković[b,c]

**Corresponding author: c.brandoni@ulster.ac.uk, T: +44 (0)28 903 68166; F: +44 (0) 28 903 68239

[a] Centre for Sustainable Technologies, School of the Built Environment, Ulster University, Newtownabbey, Co Antrim BT370QB, UK

[b] Faculty of Engineering, University of Rijeka, Croatia, Vukovarska ul. 58, 51000, Rijeka, Croatia

[c]UNECE Regional Adviser on Environment (retired), Geneva, Switzerland

e-mail: branko.bosnjakovic@bluewin.ch

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

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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.

Keywords: *water energy nexus; renewable technologies; wastewater treatment; Sub-Saharan Africa, socio-political security; HOMER*

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 annualised
def	deferrable loads
el	electrical
grid, sales	sold to the grid
proj	project

Highlights

- The benefits of integrating renewables in wastewater treatment plants are studied.
- A case study in Sub Saharan Africa is analysed with the aid of HOMER.
- The investment is cost-effective if the real cost of electricity is considered.
- Renewables can cover up to 55% of electricity demand for a conventional facility.
- In a wastewater treatment facility with water reuse this reduces to 13%.

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 at 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 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, 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, 2016).

Sub-Saharan Africa is the most electricity-poor region in the world; according to the 2015 World Energy Outlook access database *(WEO, 2015),* 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, 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 providing evidence of the knowledge gaps that justify the present work. A growing number of studies are focusing on the wastewater and energy nexus *(Wells et al., 2014),* since understanding the interactions between wastewater and energy will help to implement more effective and efficient infrastructure systems *(Plappally, 2012)*.

Wastewater and energy are closely linked: energy is necessary for wastewater distribution, usage and treatment; and wastewater contains energy in different forms: kinetic, potential, and thermal and chemically-bound energy *(Lazarova et al., 2012).* The kinetic energy of water depends on its flow rate and can be exploited through turbines *(Gallagher et al., 2015),* Archimedean screws or water wheels. Potential energy is limited in the contribution that it can provide, and is generally neglected, while the thermal energy content is expected to have interesting applications for space heating *(Nowak et al., 2015).* Chemically-bound energy has recently emerged as an energy form that could potentially be used to meet the entire energy demands of conventional wastewater treatments *(Hao et al., 2015)*. The value of chemically-bound energy can be calculated as a function of the organic content (i.e. chemical oxygen demand), and is roughly equal to 3.49 kWh per kg of chemical oxygen demand. To provide an idea of the amount of energy that can be potentially produced from wastewater, a recent study conducted on a German wastewater utility calculated values of 16 kWh/(person year) for potential energy, 6 kWh/(person year) for kinetic energy, 509 kWh/(person year) for thermal energy and 146 kWh/(person year) for chemically-bound energy *(Lazarova et al., 2012)*.

Anaerobic digestion combined with Combined Heat and Power, CHP, plants is currently the most widely-applied technology for electricity and thermal production *(Silvestre et al., 2015);* however, the percentage of chemical energy that can be recovered is lower than the energy needs of the facility. The current trend is to design wastewater treatment facilities that reduce *(Li et al., 2016)* or recover energy *(Mo and Zhang, 2013)* together with chemicals, such as nitrogen and phosphorous, that can be used as agricultural fertilisers *(Chen and Chen, 2013).* This concept is of particular interest for less developed countries, like Sub-Saharan Africa where electricity access in some regions is lower than 40% and the cost of fertilisers is higher than in other regions of the world *(Morris, 2007).* Wastewater is a valuable resource since 99.5% of its volume is water; therefore, its reuse furthermore reduces the discharge of wastewater into water bodies *(Morera et al., 2016).* Although the energy requirements are generally high, wastewater reuse represents a solution for areas where the water system is already under stress due to rapid urbanisation and a high risk of extreme events in response to climate change.

Treating and reusing wastewater in Sub-Saharan Africa requires the identification of sustainable solutions to satisfy the energy needs required for these processes. Two possible pathways exist: i) to introduce wastewater treatment facilities that are capable of recovering or even producing energy, and ii) to apply renewable technologies to exploit the advantages of co-optimised investment in water and renewable energy.

The *first pathway* is the most promising but requires additional effort from research and industry, since technologies that are able to significantly reduce and fully satisfy the energy needs of a wastewater treatment facility are not yet deployable at full scale; indeed, some of these technologies are only in the pre-commercial phase. With respect to this promising pathway and water reuse, it is worth mentioning anaerobic membrane bioreactors and microbial electrolysis cells. Termed AnMBR, this option is an example of an energy generation solution based on a combination of anaerobic digestion and membrane separation, which provides a high quality of effluent. AnMBRs have a small footprint, thanks to their ability to contain a high concentration of solids. Although several aspects such as membrane fouling still need to be investigated further, the main advantage of AnMBRs is their efficient recovery of resources, including nutrients such as nitrogen and phosphorous *(Shoener et al., 2014).* Microbial electrolysis cells, a type of microbial fuel cell, are currently being assessed for municipal water and wastewater treatment markets in the EU, and it is expected that the first generation of microbial electrolysis cell electrolysers will be ready within 1-4 years *(Escapa et al., 2014).* The use of microbial electrolysis cells for wastewater treatment was first proposed in 1991 and several studies have been performed since *(Gil-Carrera, 2013).* A 12 month pilot project recently carried out in the UK reported promising results (EC, 2013). Although microbial electrolysis cell can remove 0.14 kg chemical oxygen demand/m^3/day compared with the 0.2-2 kg chemical oxygen demand/m^3/day removed by current activated sludge systems, microbial electrolysis cells also offer the advantage of producing hydrogen.

The *second pathway* represents a goal that is achievable in the short-term, since renewable energy sources have high potential, especially in Africa, and most of the technologies are at a mature phase. In this pathway, renewable technologies can be introduced into decentralised and semi-decentralised wastewater treatment facilities, in order to help the electricity grid to satisfy the energy demand of wastewater treatment and reuse. While numerous studies have assessed the benefits and problems associated with introducing renewable technologies in developing countries *(Chauhan and Saini, 2016),* to the best of the authors' knowledge, none have focused on satisfying the energy demands of a wastewater treatment facility. Furthermore, research into the wastewater and renewable energy nexus has mainly focused on a single wastewater treatment technology that also provides a source of renewable energy, like anaerobic digesters, while very few studies *(Schäfer et al., 2015)* have contributed to the discussion on the integration of different renewable technologies and wastewater treatment facilities and their management. The present work focuses on this latter approach, taking a hypothetical wastewater system in Sub-Saharan Africa as a reference. Furthermore, this study provides an insight into the reasons for and impact of such a solution in the context of the socio-political security of river basin areas in Africa.

The authors' contribution mainly comprises four aspects: i) analysis of the integration of three different renewable energy technologies (i.e. solar photovoltaic, internal combustion engines fuelled by biogas, wind turbines) to satisfy the electricity demand of wastewater treatment facilities in arid regions of less developed countries; ii) cost and benefit analysis of introducing renewable technologies into wastewater treatment facilities in less developed countries, by comparing the net present cost and the levelised cost of energy of the renewable technologies with conventional energy generation; iii) assessment of the potential coverage of the electrical loads from local renewable sources; and iv) a discussion of the impact of applying the proposed technical solutions on human security on the wider scale.

3. Methods

In the literature, varied materials and methods have been considered to explore the water and energy nexus. Several studies have been based on life cycle analysis accounting for emissions, water and land impact on a "cradle to grave" basis, considering all stages from raw material extraction, manufacturing, to end-life disposal. *Shao et al. (2013)* used life cycle analysis to assess embodied energy for ecological wastewater treatment by tracing back each stage of the production process. *Pfister et al. (2011)* employed life cycle analysis to assess water production by different power production technologies. *Li et al. (2012)* performed an input-output hybrid life cycle analysis to assess the water consumption and carbon footprint of wind power generation facilities in China. Other studies have analysed the water and energy nexus using supply chain analysis, including *Pan et al. (2012)* who investigated the water and energy nexus of coal power plants in China. *Shao and Chen (2015, 2016)* compared the resource utilization efficiency of a constructed wetland wastewater treatment system, using an input output analysis to account for embodied exergy and energy.

The approach used in this paper differs from previous studies. Our aims were to assess the benefits of incorporating renewable energy technologies into wastewater treatment facilities, and by identifying the optimal configuration of renewable technologies. Rather than analysing the ecological footprint of a specific wastewater treatment process, this work seeks solutions that employ local renewable energy sources to satisfy the electrical demand of wastewater treatment plants in arid and electricity-poor regions, to reduce the carbon footprint of the plants. The analysis is based on HOMER, a software package developed by the US National Renewable Energy Laboratory, which enables comparison of different energy systems on the basis of their technical and economic merit *(Lambert et al., 2006).*

HOMER is a simulation and optimization toolbox that models the hourly performances of different system configurations, allowing the user to identify the optimal combination that satisfies the technical constraints at the minimum net present cost. The software is intended to assess micro-generation systems that generate electricity and heat to serve a nearby load. Such systems can be isolated or connected in parallel to the grid, and be composed of renewable and/or conventional technologies (i.e. diesel engines) and storage technologies. HOMER can model any micro-generation system, such as photovoltaic units, wind turbines and Combined Heat and Power units, and provides a wide library of self-defined systems that can be chosen by the modeller. The software has been developed to address the challenges generally encountered in the simulation of micro-generation systems, such as the large number of design options and the uncertainty of key parameters, and allows the user to develop a sensitivity analysis by performing multiple optimizations of the design systems under a range of defined parameters.

The simulation process determines the feasibility of the specific configuration, demonstrating if the proposed solution is able to serve the electrical and thermal loads and satisfy the constraints imposed, and estimates the total cost of installing and operating the system. In the case of renewable energy technologies, HOMER can help to decide what to do with the surplus electricity from renewable sources in times of excess and how best to generate additional power. HOMER uses a cost-based dispatch logic regardless of configuration. It determines whether renewable energy sources are able to satisfy the load, and if not, identifies the optimal dispatchable system that can meet demand on the basis of minimisation of the fixed and marginal cost.

This analysis of the wastewater and renewable energy nexus in the context of water treatment and reuse is based on a typical wastewater treatment facility in a Sub-Saharan urban area. Selection of a specific location is necessary to define the resources available for renewable energy production. Bahir Dahr, an urban town in north-western Ethiopia, has been selected as a reference. The area has its own pipe sewage system and is currently suffering from severe water pollution mainly due to unsustainable industrial and agriculture practices, the effects of which have been aggravated by climate change and population growth *(Wosnie and Wondie, 2014).*

In this paper we refer to a typical wastewater treatment facility, which is generally composed of different sections designed for a specific function, as shown in Fig. 1. A primary treatment (pre-treatment) section removes solid materials, and wastewater is screened, measured and the main debris removed. A secondary treatment section removes organic matter, as well as the nitrogen and phosphorous content. This section consists of a primary clarifier, in which organic matter is physically removed, combined with a biological treatment, and represents the core of the system. Frequently, a secondary clarifier follows the primary clarifier. The sludge coming from the first and second clarifiers is generally sent to an anaerobic digester for the production of biogas to generate electricity and thermal energy. Finally, tertiary treatments can be added to improve the quality of the treated wastewater, especially when the reuse is intended for drinking or irrigation. The biological treatment is generally a bioreactor that converts the biological oxygen demand to bacterial biomass. The most widespread biological treatment used in commercial plants is conventional activated sludge technology.

The choice of the biological treatment strongly depends on the quality of the influent and effluent. The present paper analyses two different cases: i) the use of a conventional activated sludge system in a standard wastewater treatment facility, and ii) the use of a membrane bioreactor to produce treated wastewater suitable for reuse in irrigation. Although membrane bioreactors have only been developed at pilot scale, they have been already experimented with in Africa *(Skouteris, 2014)* and the technology has been demonstrated to provide a quality of effluent suitable for reuse as irrigation water. Moreover, membrane bioreactors are also characterised by the highest energy requirements, providing the worst-case scenario in terms of energy demand *(Krzeminski et al., 2012).* The techno-economic analysis was performed in three main steps, as described below.

Step 1: Definition of the daily and seasonal water profiles of the wastewater treatment facility serving the population

Starting with the total withdrawal per capita reported in *FAO (2015),* seasonal and daily variations have been assumed. In the area under analysis, three main seasons can be considered: a rainy season from March to August; a transition season from September to October characterized by low rainfall, and a drought season from November to April *(Mushir, 2012).* The daily trend has been derived from the literature and scaled according to the average seasonal water withdrawal value *(Quasim, 1998).* The water flow trends experienced by the facility are illustrated in Figure 2a, with the wastewater facility assumed to treat 793,356 m^3 of water per year.

Since the treatments for water reuse strongly depend on the characteristics of the wastewater, the main parameters of the influent wastewater have been identified from the available literature, and are summarized in Table 1.

Step 2: Definition of energy load profiles for the wastewater treatment facility

Once the daily profiles of the wastewater to be treated have been defined, the electricity demand must be calculated. The amount of energy required by different wastewater treatment plants varies widely, but the average energy demand, expressed in kWh per m^3 of treated wastewater, can be estimated according to the technology chosen *(Logan, 2008)*.

The wastewater treatment facility under analysis follows the scheme reported in Fig. 1. In the water reuse case, the conventional activated sludge system is replaced with a membrane bioreactor. Average energy demands of 0.5 kWh/m^3 *(Bodik and Kubaská, 2013)* and 3.7 kWh/m^3 *(Skouteris et al., 2014)* have been considered for the facilities based on the conventional activated sludge system and membrane bioreactor, which correspond to approximately 402 MWh/year and 2,945 MWh/year, respectively. Figure 2b shows the electrical profiles; it is worth noting that calculation of hourly values is necessary to account for the variability of intermittent renewable energy sources.

Step 3: Techno-economic assessment of various renewable energy solutions for the wastewater treatment facility using HOMER

Once the electrical energy profiles had been defined, the HOMER software tool was used to assess the suitability of various renewable energy systems. HOMER identifies the best configuration on the basis of the minimum net present cost (Eq. 1), which represents the life cycle cost of the system. In contrast to a life cycle costing approach *(Shao et al., 2016)*, the life-cycle cost provided by HOMER considers the cost of installing and operating the system over its lifespan, and includes all costs and revenues, with future cash flow discounted to the present. It is possible to specify the discount and inflation rate, as well as the project lifetime; a project lifetime of 25 years, annual discount rate of 8% and expected inflation rate of 2% were assumed. The net present cost includes the cost of the initial capital, cost of replacing components, maintenance and all the operating costs during the lifetime of the project. In the net present cost, costs are positive and revenues are negative, having the opposite sign of the net present value. All the costs are in US dollars. The net present value, and therefore the net present cost, is one of the most widely-used capital budgeting methods for evaluating investment projects.

$$NPC = \frac{\sum C_{ann,tot}}{CRF \cdot R_{proj}} \tag{1}$$

where $C_{ann,tot}$ is the total annualized cost (\$/yr), *CRF* is the capital recovery factor, and R_{proj} is the project lifetime expressed in years. The CRF is the figure generally used in capital budgeting to calculate the present value of an annuity (Eq.2):

$$CRF\ (i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{2}$$

where i is the real interest rate and N is the number of years considered for recovery of the investment.

The life cycle cost is used to calculate the cost of energy (Eq. 3), which represents the levelized cost of energy, defined as the ratio between the total annualized cost, $C_{ann,tot}$, of the system and the energy produced. Cost of energy is a useful parameter that is generally applied to compare different energy technologies *(Peterson and Fabozzi, 2012)*, and is calculated as shown in (Eq. 3).

$$COE = \frac{C_{ann,tot}}{E_{prim} + E_{def} + E_{grid,sales}} \tag{3}$$

where E_{prim} *and* E_{def} are the total amount of primary and deferrable load, respectively, and $E_{grid,sales}$ is the energy sold to the grid. These three energy terms represent the total amount of useful energy that the system produces per year. The levelized cost of energy is the average cost for each kWh of useful electrical energy produced by the system. It is worth noting that all comparisons that HOMER establishes between different configurations are based on the net present cost, since - in the literature - the definition of the levelised cost of energy is more disputed than the definition of the net present value *(Lambert et al., 2006).*

4. System modelling

As previously introduced in section 1, it is assumed the renewable energy technologies are in parallel to the main electricity grid (see Figure 3), since the electrification rate in urban areas of Sub-Saharan Africa is over 60% with several electrification projects currently under development *(Zeyringer et al., 2015).* Figure 3 summarizes the alternative renewable systems considered in this study, which included a Combined Heat and Power system fuelled by biogas produced from the wastewater sludge, photovoltaic units, and wind turbines. The electricity load is AC-coupled to the electricity grid, as well as the wind turbine and combined heat and power units, while the photovoltaic units and batteries are DC-coupled. An internal combustion engine, ICE, in cogeneration mode was assumed to be able to produce energy using the biogas coming from the anaerobic digester. This is one of the most commonly applied configurations worldwide, since the heat recovered by the combined heat and power unit is used to satisfy the heat demands of the anaerobic process *(Silvestre et al., 2015)*.

The sizes of the combined heat and power unit and photovoltaic system were varied in steps of 5 kW_{el} from 0 kW_{el} up to the peak load. A step size of 10 kW_{el} was chosen for the wind turbine system. Table 2 presents the main techno-economic data for the renewable technologies assessed; most of this information was derived from default data available in the HOMER library. Clearly, the technology lifetime varies for each renewable system, ranging from 48,000 hours for the internal combustion engine (almost 6 years considering 8600 operating hours) to 25 years for a photovoltaic system. For the internal combustion engine modelled in HOMER, the loss in electrical efficiency when working at partial loads has also been considered; at the minimum load ratio of 40%, electrical efficiency drops from 38% to 35%. The use of photovoltaic units requires a DC to AC converter (Fig. 3). A default converter has been considered. The capital cost has been assumed to be \$300, with a lifetime of 15 years, inverter efficiency of 90% and rectifier efficiency of 85%.

4.1 Resource assessment

The natural resources used for energy production need to be defined by the modeller. The renewable energy resources considered in the present analysis are wind energy, solar energy and biogas. HOMER provided data on solar insolation and wind speed, which was obtained via the internet from international meteorological centres. The annual average wind speed for the reference location is 3.7 m/s at an anemometer height of 50 m. Figure 4 shows the monthly average wind speed for the specific location. The variation in wind speed, which is given by the autocorrelation factor, is 0.85, with 15 hours of peak wind speed and a diurnal pattern strength (i.e. the magnitude of the average daily pattern of wind speed) of 0.25.

For photovoltaic production, a typical meteorological year is considered for the specified location. The annual solar radiation at the latitude of 8^{o} 58.8’N and longitude of 38 ^{o}45.5’E is 5.81 kWh/m^2/day with an average sky clearness of 0.68 (Fig. 5). As expected, solar radiation is available throughout the year, with a high potential for electricity production from solar energy of 2,306 kWh for each kW_{el} of photovoltaic unit installed.

Biogas produced from the organic content of the wastewater passing through the anaerobic digestion system has also been considered. The quantity of biogas produced has been defined as the fraction of the chemical oxygen demand removed during wastewater treatment (Table 1). Figure 6 shows the biogas monthly resource input, which has been defined according to Eq. 4.

$$\begin{aligned}&Biogas\ availability\\&= WW\ available \times \frac{COD}{WW\ treated} \times COD\ removal\ efficiency\\&\times \frac{biogas\ produced}{COD\ removed}\end{aligned}$$

(4)

A chemical oxygen demand removal efficiency of 70% is assumed *(Khiewwiji et al., 2015)*. These data were used by HOMER to generate an annual series of biogas hourly available for electricity production.

When the electricity needs of the wastewater treatment facility are not satisfied by renewable energy sources, the Ethiopian energy mix has been considered, whereby - on average - 88% of electricity comes from hydropower, 11% from diesel generators and 1% from geothermal energy *(Energypedia, 2016).* We have not taken any thermal needs into consideration, but have assumed the thermal energy produced by the biogas unit is entirely used internally for the anaerobic digestion process. In emergencies, electricity cannot be provided by the central grid. It is assumed that a diesel engine will be used in such situations. Table 3 summarizes the main characteristics of the energy resources considered in this analysis.

4.2 Scenarios analysed

Three different scenarios (Table 4) have been analysed: i) baseline, ii) emergency, and iii) “selling electricity back” scenario. The baseline scenario takes three different electricity tariffs into account. The current electricity tariff in Ethiopia is 0.04 $/kWh, which is one of the lowest and most subsidised rates in Sub-Saharan Africa *(Bekele and Tadesse, 2012).* Since the current cost of electricity is not representative of the true cost of electricity and is underestimated by 50% *(Foster and Morella, 2011),* a tariff of 0.08 $/kWh has been considered in the baseline scenario. Finally, a tariff of 0.16 $/kWh is also used in the baseline scenario, which represents the long-term marginal cost of power when the costs of building and operating an effective full coverage transmission and distribution network in Ethiopia is considered *(Foster and Morella, 2011)*. For the baseline scenario, it is assumed that excess electricity cannot be sold back to the national grid, since at a low voltage this would require the systems to be supplemented with additional safety provisions.

Considering there are approximately 40 days (*Foster and Morella,* 2011) of power outage in Ethiopia per year and wastewater treatment cannot be stopped, an emergency scenario has been analysed, in which electricity is produced for 40 days per year by a diesel engine at a tariff of 0.9 $/kWh *(Bekele and Tadesse, 2012*). Finally, a selling tariff of 200 US$/MWh for the electricity sold back to the grid, has been considered ("selling electricity back" scenario). It is equal to the feed in tariff currently provided by the government of Kenya for supporting the photovoltaic production *(Kebede, 2015).*

5. Results and Discussion

Table 5 presents the technical results of the simulations developed by HOMER in three scenarios for a wastewater treatment facility with a conventional activated sludge system situated in Sub-Saharan Africa. The table presents the size, number of operating hours and electricity produced by the various renewable technologies considered in the micro-generation system, as follows: i) an internal combustion engine fuelled by biogas produced in the wastewater treatment plant; ii) photovoltaic units; and iii) a wind turbine. The energy capacity of lead acid batteries is also shown. The results are ordered from minimum to maximum net present cost, the main criterion employed in the HOMER analysis. Table 6 summarises the main economic parameters for the solutions identified, including initial investment, cost of energy and net present cost. Table 6 also shows the renewable fraction from local resources, the amount of electricity purchased, the amount of biogas used by the internal combustion engine and the surplus electricity coming from intermittent renewable sources (i.e. wind and solar energy). It is worth noting the renewable fraction only considers local renewable energy sources. In fact, as mentioned above, 89% of the electricity supplied by the national grid in Ethiopia is generated from renewable sources.

5.1 Solutions for a wastewater treatment facility with a conventional activated sludge system

The HOMER analysis indicates that, at the current Ethiopian electricity tariff of 0.04 \$/kWh, investment in renewable technologies is not economically viable. At this subsided tariff, purchasing electricity from the grid is the best option from an economic point of view. For this solution (solution A), the net present cost shown in Table 6 is determined from the Operating and Maintenance, O&M, cost of the grid. The first solution with a renewable energy system (solution B) proposed by HOMER is a 5 kW_{el} internal combustion engine fuelled by biogas, which would slightly increase the levelised cost of energy to 0.041 \$/kWh, and cover 11% of the electrical load. The investment required for solution B is \$7,500, and there is no excess electricity that is not used by the wastewater treatment facility.

These predictions for a wastewater treatment facility located in a specific location of Ethiopia are in line with the literature. *Bekele and Tadesse (2012)* argued that the use of renewable technologies for electricity production in an Ethiopian district is not profitable at the current electricity tariff of 0.04 \$/kWh. Therefore, a higher tariff that takes into account the true cost of electricity is necessary to make the use of local renewable energy sources economically desirable. At an electricity tariff of 0.08 \$/kWh, several possible configurations of renewable energy technologies are characterised by a lower net present cost and lower levelised cost of energy than conventional energy generation. The minimum net present cost is achieved for solution A, a 15 kW_{el} internal combustion engine fuelled by biogas. The size of the internal combustion engine is limited by the maximum amount of biogas available from wastewater treatment. The internal combustion engine works 8,760 hours per year, highlighting the convenience of using biogas for electricity generation *(Hao et al., 2015)*. In this solution, approximately one-third of the electricity demand can be supplied by local renewable energy sources.

A slightly higher cost of energy, 0.070 \$/kWh, is predicted for a higher fraction from local renewable sources (35%). HOMER identifies solution B, a combination of a $15kW_{el}$ biogas system and a $5kW_{el}$ photovoltaic system, which is able to produce 11,531 kWh per year, operating for 4,469 hours.

A further suggested system, solution C, with a cost of energy of 0.074 \$/kWh, is the combination of a $15kW_{el}$ internal combustion engine fuelled by biogas with a 10 kW_{el} wind turbine. In this solution, the amount of electricity produced from local renewable sources is slightly lower than for solution B (33.3%), since the 10 kW_{el} wind turbine produces less energy (2,656 kWh per year) than a 5 kW_{el} photovoltaic unit, due to the characteristically high level of solar radiation in the area. The last solution identified by HOMER, solution D, suggests the integration of a 15 kW_{el} biogas system with a 5 kW_{el} photovoltaic unit and 10 kW_{el} wind turbine. The investment cost and net present cost increase; however, this combination of three micro-generation units provides a higher renewable fraction of 36%. Although solution D works for the same number of operating hours thorough the year as solution A, the $15kW_{el}$ internal combustion engine produces slightly less electricity in solution D. This indicates the internal combustion engine is modulated to allow all of the energy produced by the intermittent renewable technologies (photovoltaic system and wind turbine) to be used by the wastewater treatment facility. In all of the cases proposed by HOMER at the 0.08 \$/kWh tariff, there is no excess of electricity produced by the intermittent renewable sources.

When the electricity tariff increases, the renewable technologies selected by HOMER change, highlighting how the results of this analysis are strongly affected by the cost of electricity from the grid. The optimal solution selected for tariff of 0.16 \$/kWh is a $15kW_{el}$

internal combustion engine fuelled by biogas combined with a 50 kW_{el} photovoltaic system (solution A). The size of the internal combustion engine does not change with the tariff, since its maximum size is limited by the amount of biogas available from the wastewater treatment facility, as previously mentioned. A larger photovoltaic system allows a 55% renewable fraction. In contrast to the previous solutions, a small amount of electricity, 3,880 kWh (around 1% of the electricity needs) is produced in excess by solution A and not used by the wastewater treatment facility. Comparing the number of operating hours for the internal combustion engine system with and without a photovoltaic unit (solutions A vs. solutions B and C), it is clear that the operating hours of the internal combustion engine reduce when it is coupled to a photovoltaic system. As shown in Fig. 7, modulating the electrical output of the internal combustion engine helps to reduce the excess electricity produced from intermittent renewable sources; when production by the photovoltaic system occurs at the highest rate, between 8:00 a.m. to 4:00 p.m., production by the internal combustion engine is drastically reduced to lessen the amount of excess electricity produced from intermittent renewable sources.

However, a battery is required to reduce the electricity in excess to zero, as shown in solution G, in which a 50 kW_{el} photovoltaic system is combined with a 15 kW_{el} internal combustion engine and a storage unit with a storage capacity of 350 kWh. While batteries remain expensive *(Wang et al., 2016)*, research in this field is active and the study of rechargeable batteries based on low-cost materials is promising. For this specific location, the maximum size of the wind turbine selected by the model is 10 kW_{el}; the size of the wind turbine is limited by the average wind speed and the trade-off between investment and the savings in operating cost.

In the emergency scenario, with 40 days covered by electricity produced by a diesel engine at a cost of 0.9 $/kWh for diesel, the investment in renewable technologies is always economically viable and desirable. For the emergency scenario, the average electricity tariff is 0.134 \$/kW, based on 40 days at 0.9 \$/kWh for diesel and the remainder of the year at 0.04 \$/kWh. The solution characterised by the lowest net present cost, solution A in Table 6, is the coupling of a 35 kW_{el} photovoltaic system and 15 kW_{el} internal combustion engine fuelled by biomass. The renewable coverage from local resources would be 48%, with a small excess of electricity of 591.5 kWh/year, which represents 0.16% of electricity needs. Table 6 also shows the other possible solutions with a levelised cost of energy lower than the true cost of electricity. The initial investment ranges from 100,000 to 160,000 US dollars, with a coverage by renewables ranging from 26% to 48%. The use of high rate photovoltaic systems of 55 kW_{el} and 50 kW_{el} increases the amount of electricity in excess (about 4% of the electricity demand), requiring the use of batteries or providing an opportunity to sell excess electricity back to the grid.

In the “selling electricity back” scenario, a selling tariff of 200 \$/MWh has been considered. As mentioned above, this value is equal to the feed-in tariff introduced by Kenya in order to support the introduction of photovoltaic systems. At the current Ethiopian electricity tariff of 0.04 \$/kWh, investment in renewable technologies is still more viable than buying electricity from the grid. However, as shown by solution C of the feed-in tariff scenario (Tables 5 and 6), coupling a 15kW_{el} biogas system with a 120 kW_{el} photovoltaic unit provides a lower levelised cost of energy than the electricity tariff, thanks to the revenues generated by selling excess electricity back to the grid. For this solution, the renewable fraction reaches 74%, with a small amount of excess electricity of 946 kWh, which is 0.2% of total electrical demand.

5.2 Solutions for a wastewater treatment facility containing a membrane bioreactor for water reuse

Tables 7 and 8 show the analyses for the case of a wastewater treatment facility with a membrane bioreactor to enable the reuse of reclaimed wastewater for irrigation. In this case, the electricity demand is more than seven times higher than a wastewater treatment facility based on a conventional activated sludge system. In the baseline scenario at the tariffs of 0.04 \$/kWh and 0.08 \$/kWh, there is no change in the size of the renewable technologies between the facilities with a membrane bioreactor and conventional activated sludge technology. As a consequence, the coverage of the electrical loads from renewable sources reduces to 5% for the wastewater treatment facility with a membrane bioreactor. In this case, the higher electricity tariff of 0.016 \$/kWh tariff justifies the introduction of a 120kW$_{el}$ photovoltaic system, which combined with a 15 kW$_{el}$ internal combustion engine and 10 kW$_{el}$ wind turbine covers 13% of the electricity needs of the wastewater treatment facility. For solution D, the batteries selected are not able to reduce the electricity in excess to zero.

As shown in Table 7, the optimal size of photovoltaic system selected by HOMER for the wastewater treatment facility with a membrane bioreactor increases compared to the case of conventional activated sludge technology. The size of the other renewable technology units cannot change, due to limitations on resource availability, although increasing the size of renewable technologies would be convenient from an economic point of view.

HOMER did not select any high rate photovoltaic system for the ‘selling electricity back” scenario for the wastewater treatment facility with a membrane bioreactor, as in the case of the conventional activated sludge facility. As shown in Table 7, the sizes of the renewable technologies selected by HOMER for the wastewater treatment facility with a membrane bioreactor are the same as for the 0.04 \$/kWh baseline case. Even a 120 kW$_{el}$ photovoltaic system would not generate any income, since all of the electricity would be used by the wastewater treatment facility with a membrane bioreactor as the total electrical demand is more than seven times higher than for conventional activated sludge technology.

6. Post-HOMER analysis of the proposed solutions in the context of socio-political and security

This section provides a post-HOMER analysis to discuss the merits of the identified technical solutions against the socio-political and security background of the region. We analyse how the technical approaches proposed in this work can contribute to simultaneously address several socio-political pressures and reduce both domestic and cross-border conflicts.

As explained in the introductory chapter, the rapidly growing population in Sub-Saharan Africa is experiencing increasing hardships due to climate change, a lack of water and electricity, and deteriorating environmental quality. All of these factors contribute – in one way or another – to both human insecurity and transboundary tensions or even conflicts. In the context of sustainable development, it has become helpful to distinguish the concept of human security from the more conventional idea of national (state) security *(Hove et. al., 2013; UNDP, 1994).* Whereas state security addresses the defence of a country within its international borders, the concept of human security focuses on the security concerns of ordinary people in their daily lives, encompassing protection from the threat of disease, hunger, lack of water, unemployment, crime, social conflict/exclusion, political repression and environmental hazards. With respect to water issues, both state and human insecurity play a key role in Sub-Saharan Africa, where some 30% of the population live in semi-arid areas *(Tiffen, 2003)*. Malnutrition is severe, food imports are increasing steadily, and food aid remains a common relief measure *(Reij and Smaling, 2008).* Rural-to-urban migration is the single most important cause of the rapid growth of the urban population of the region; over 70% live in urban slum dwellings that lack sanitation and other basic services *(Hove et al., 2013).*

Much of the highest population growth is occurring in places that are already vulnerable to water scarcity, with climate change aggravating the scarcity of water, cropland

and pasture. Resource scarcity will likely increase its weight as a motivation for violent conflict over time *(Matthew, 2012)*. Policies related to agriculture, food subsidies and exchange rates have tended to keep food prices low for urban consumers, but at the expense of farmers *(Hove et al., 2013; IBRD, 1989)*. Largely due to these policies, the level of urbanization in Sub-Saharan Africa has increased dramatically and is currently almost 40%. The UN Population Fund projected the urban population of Africa will double between 2000 and 2030 *(UNFPA, 2007)*. According to some estimates, the situation in Sub-Saharan Africa is even more worrying: the urban population of the region doubled between 2000 and 2015, and over half of this population cooks on open fires or inefficient stoves using fuel wood, charcoal or dung, resulting in high levels of indoor pollution and severe health impacts. Moreover, in 2015, 66% of the urban population in Sub-Saharan Africa did not have water piped onto their premises, representing a small increase from only 57% in 1990 *(Satterthwaite, 2015)*.

As pointed out by many researchers, the electrical power infrastructure in Sub-Saharan Africa is significantly underdeveloped, leading to deficits in energy access, installed capacity, and per capita consumption *(Castellano, 2015)*. Countries with electrification rates of less than 80% exhibit reduced GDP per capita. The level of electricity-access in Sub-Saharan Africa is the poorest in the world, with 48% of the population lacking access. According to *Castellano (2015),* it takes an average of 25 years to progress from an electrification rate of 20% to 80%.

Conflicts may be domestic – restricted to one country – but, as is the case for water issues, a variety of transboundary conflicts can occur; such conflicts concern both water quantity and water quality, often in connection with food production and energy supply issues. How can the integration of renewable energy sources with wastewater treatment facilities, as proposed in the earlier sections of this work, contribute to mitigate the security risks related to the water-energy nexus in Sub-Saharan Africa?

Firstly, the HOMER analysis indicates renewable energy sources can cover up to 55% of the electricity demand for standard wastewater treatment facilities in this region. This approach could help to overcome one of the major barriers to the implementation of wastewater treatment facilities, a lack of energy. Protecting water bodies from direct wastewater discharge and avoiding a high incidence of water-borne diseases will help to maintain social cohesion and stability, especially under conditions of prevailing poverty, extremely rapid population growth, and migration from rural to urban and semi-urban areas. Therefore, introduction of the proposed waste-water technologies in urban and semi-urban areas can also be justified from a security perspective.

Secondly, lack of electricity is more than just an inconvenience – it can be life-threatening. Large numbers of schools and health centres operate without electricity. Without proper health and education, the chances of the population escaping poverty remain slim to none. However, an electricity infrastructure can only be deployed and operated in a financially-sustainable electricity sector that can recover its costs, make investments, provide electricity reliably and meet social and environmental obligations. The HOMER analysis demonstrates renewable energy sources are techno-economically viable solutions, even when considering the true cost of electricity or typical days of power outage per year. Furthermore, the proposed integration of renewable energy sources in wastewater treatment facilities may improve the resilience of the energy system, providing a solution for the days of power outage at a levelised cost of energy lower than the electricity tariff.

Thirdly, a positive impact on human security arises from the growth in jobs. Any technology, whether built by foreign or local contractors, plays a significant role in the capacity-building of local actors. Both wastewater and renewable energy technologies comprise civil, hydraulic, mechanical and electrical (electromechanical) engineering structures. Therefore, the stakeholders, experts, contractors, consultants, labourers, small business and microenterprises will have the opportunity to build capacity either during the manufacturing and installation phase or during operating and maintenance. Renewable energy generation can increase local employment; typical employment factors for solar photovoltaic systems are 25 people/MW for manufacture and installation, and 2.5 jobs/MW_{el} for operation and maintenance *(Brandoni et al, 2016).*

Fourthly, the proposed integration is capable of mitigating certain cross-boundary impacts, both in terms of water quantity and quality. Although the proposed techno-economically viable solutions can only cover 13% of the total electrical demand in the case of water reuse, the integration of renewable technologies into wastewater treatment facilities can attract new investors, providing access to both adaptation and mitigation funds *(Climate Investment Fund, 2014)*. Water reuse offers an alternative for the development of small-scale irrigation schemes, without the construction of storage systems that could be a further source of potential conflict. Considering an irrigation need of 4,200 m^3 per ha (*Maton et al., 2010*) and a cultivated area per person of 0.17 ha *(Home and Sale, 2011),* a wastewater treatment facility serving 10,000 people produces enough water to irrigate a cultivated area of approximately 190 ha, which could feed about 1,100 people for 41 days. This is a significant contribution that could contribute to locally relieve the food insecurity of the impoverished and dissatisfied urban and semi-urban population. *Rockström et. al.* (2010) argued the local catchment scale offers the best opportunities for water investments to build resilience in small-scale agricultural systems and address trade-offs between the use of water for food and other ecosystem functions and services. The Abay (Blue Nile) drainage basin covers 180,000 km^2 (20% of Ethiopia's land area) and is home to around 20 million people. The water flow in the Blue Nile averages 48 billion m^3 at the Sudanese border *(Johnston and McCartney,* *2010).* The potential water quantity savings from the Blue Nile can be calculated by assuming a wastewater treatment facility servicing a population of 10.000, treating 0.8 million m^3/year and yielding the same amount of irrigation water to avoid diverting the same amount of water from other sources. If all inhabitants of the Blue Nile drainage basin could make use of such facilities, 12% of total irrigation needs would be satisfied, equalling an upper limit of 1.6 billion m^3/year to be saved, or 3.3% of the total flow of the Blue Nile at the Sudanese border. While this volume is not dramatic, it carries moral significance as a confidence building measure in the context of transboundary negotiations between upstream and downstream countries. Moreover, the provision of wastewater treatment facilities area-wide would presumably have favourable impacts on health and environment, not only locally but also cross-border downstream.

Precise assessment of the positive effects of deploying the proposed integration of renewable energy technologies with wastewater treatment facilities in Sub-Saharan Africa depends on a number of external unknowns. Reliable basic data are not available on the processes and consequences of ongoing urbanization; on the extent of - and obstacles to - deployment of treated water for irrigation; on environmental and health impacts, both locally and downstream due to the lack of solid waste management and wastewater treatment facilities; and the fact a financially sustainable electricity sector is still lacking, preventing steady deployment of renewable energy technologies. To address security issues, the sharing of information at all levels is of utmost importance. The obligation to share data and information on a regular basis is a principle of international customary water law, which is definitively expressed in water-related conventions. Studies on cooperation in African river and lake basins show formal information-sharing agreements are often preceded by projects designed to improve the information basis *(Wirkus and Böge, 2006).* The ability to access accurate information increases the likelihood of agreements that are technically and economically feasible, deliver their promised benefits and produce no significant negative side-effects (or even unexpected positive outcomes). Joint research involving several stakeholders is likely to result in fewer technical controversies than research by individual stakeholders.

7. CONCLUSIONS

This work investigated the benefits of integrating renewable energy technologies with a wastewater treatment facility located in arid regions of water-stressed urban areas. An urban area of Sub-Sahara Africa has been selected to accurately consider the electrical loads of a wastewater treatment facility based on a conventional activated sludge system and a wastewater treatment facility based on a membrane bioreactor so the treated water can be reused for irrigation.

The HOMER analysis showed the introduction of technology that harvests local renewable energy sources to satisfy some of the electrical load of a wastewater treatment facility is cost-effective if the true cost of energy is considered or if the costs of covering the days of power outrage is taken into account. The integration of renewable technologies is predicted to provide good coverage of the electrical load required by a wastewater facility based on a conventional activated sludge system, achieving a 33% renewable fraction at an electricity tariff of 0.08 $/kWh (true cost of electricity considering the current transmission and distribution network), 55% at an electricity tariff of 0.016 $/kWh tariff (true cost of building and operating an effective full coverage transmission and distribution network in Ethiopia), 48% in the emergency scenario, and up to 74% if a selling back electricity price of 200 $/MWh is considered.

Currently, less than 30% of wastewater is treated in Sub-Saharan Africa. This work highlights the fact that integration of renewable energy technologies would help to overcome one of the main barriers to the widespread deployment of wastewater treatment facilities, which is a lack of electricity. The emergency scenario shows the predicted solution could also help to improve the reliability of the electrical grid at a levelised cost of energy lower than the cost of using diesel engines to satisfy the electrical demands of the facility during power outages. Furthermore, in all of the solutions identified, even those with a high renewable fraction, the electricity in excess is never greater than 4% of the electrical demand. Therefore, the developments proposed in this work would have minimal impact on the national electricity grid.

In the case of water reuse, the cost-effective solutions selected by HOMER cover a smaller percentage of the electricity needs of the wastewater treatment facility with a membrane bioreactor (up to 13%). This is mainly associated with the high electrical demand of treating wastewater for reuse, the constraints affecting some local renewable energy sources (i.e. biogas) and the high investment cost of renewable technologies. However, as explored in section 6 of this paper, adoption of the proposed technologies may exert several positive impacts on communities, such as the mitigation of security risks at both the domestic and cross-border levels.

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Table 1. Main parameters of the influent wastewater *(Henze, 2002; Khiewwijit et al., 2015)*

COD [mg/L]	500
SS [kg/(person*year)]	20
CH_4 [g/gCOD$_{removed}$]	0.23

Table 2. Main techno-economic data for the renewable technologies assessed

CHP unit – Internal Combustion Engine	
Electrical efficiency [%]	38
Thermal efficiency [%]	50
Lifetime (hours)	48,000
Minimum load [%]	40
Capital cost ($/kWh)	1,500
O&M costs ($/kWh)	0.021
PV systems	
Efficiency [%]	17
Capital cost ($/kW)	2,500
Lifetime	25
Wind system (Generic 10kW)	
Power output (kW)	10
Capital cost ($/unit)	20,000
Lifetime	20
Batteries (Generic 1kWh Lead Acid)	
Nominal voltage [V]	12
Nominal capacity [Ah]	83.3
Cost ($/kWh)	300
Lifetime (kWh)	800

Table 3. Main characteristics of the energy resources considered in this analysis

Resources	***Description parameters***
Biogas	Low heating value of 5.5 MJ/kg
Solar energy	Solar radiation of 5.81 $kWh/m^2/day$, clearness factor of 0.60
Wind	Average wind speed of 3.7 m/sec
Local energy mix for electricity supply	88% hydropower, 11% diesel, 1% geothermal energy
Diesel for emergency scenario	0.9 $/kWh

Table 4. Scenarios analysed

	Electricity prices	*Electrical demand [MWh/year]*		*Water treated [m^3/year]*
		Conventional Activated Sludge	*Membrane bioreactor*	
Baseline Scenario	0.04 \$/kWh 0.08 \$/kWh 0.16 \$/kWh	402	2,945	793,356
Emergency Scenario	0.04 \$/kWh 41 days @ 0.9\$/kWh			
"Sell electricity back" scenario	0.04 \$/kWh Selling tariff of 0.2 \$/kWh			

Table 5. Simulation results in three scenarios for a wastewater treatment facility with a conventional activated sludge system (Nominal power, working hours and electricity production of micro-generation technologies)

Baseline scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
0.04$/kWh										
A										
B		5			8,760			43,800		
0.08$/kWh										
A		15			8,760			131,337		
B	5	15		4,469	8,760		11,531	131,316		
C		15	10		8,760	4,698		131,271	2,656	
D	5	15	10	4,469	8,760	4,698	11,531	131,240	2,656	
0.016 $/kWh										
A	50	15		4,469	8,234		115,306	119,763		
B	45	15	10	4,469	8,378	4,698	103,775	122,093	2,656	
C		15			8,760			131,337		
D		15	10		8,760	4,698		131,217	2,656	
E	70			4,469			161,428			
F	65		10	4,469		4,698			2,656	
G	50	15		4,469	8,234		115,306	119,763		350
Emergency scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
A	35	15		4469	8,195		80,714	122,364		
B	35	15	10	4469	8,156	4689	80,714	121,273	2,656	
C		15	10		8,695	4689		130,382	2,656	
D	55			4469			126,837			
E	50		10	4469		4689	115,306		2,656	
"Selling electricity back" scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
A										
B		5			8760			43,800		
C	120	15		4469	8760		276,735	131,400		

Table 6. Simulation results in three scenarios for a wastewater treatment facility with a conventional activated sludge system (Economic results, electricity purchased, biogas consumption, renewable fraction, excess electricity)

Baseline scenario							
Solutions	*Initial investment [$]*	*COE [$]*	*NPC [$]*	*Electricity purchased [kWh]*	*Biogas [kg/year]*	*Renewable fraction [%]*	*Excess electricity [kWh]*
0.04$/kWh							
A	/	0.040	208,185	402,601	/	/	/
B	7,500	0.041	212,276	358,801	31	11.0	/
0.08$/kWh							
A	22,500	0.069	360,762	271,264	94	32.6	/
B	36,500	0.070	365,214	260,907	94	35.2	/
C	42,500	0.074	386,253	268,673	94	33.3	/
D	56,500	0.075	390,717	258,327	94	35.8	/
0.016$/kWh							
A	159,500	0.116	601,521	182,555	86	55.0	3,880
B	165,500	0.120	625,232	187,211	88	53.5	3,063
C	22,500	0.123	641,303	271,264	94	32.6	/
D	42,500	0.128	664,115	268,273	94	33.3	/
E	191,500	0.147	766,408	270,825	/	32.7	15,011
F	197,500	0.152	789,978	279,931	/	31.5	12,105
G	264,500	0.160	831,952	182,555	86	54.7	/
Emergency scenario							
Solutions	*Initial investment [$]*	*COE [$]*	*NPC [$]*	*Electricity purchased [kWh]*	*Biogas [kg/year]*	*Renewable fraction*	*Excess electricity [kWh]*
A	119,000	0.094	487,289	208,126	88	48	591.5
B	139,000	0.098	509,417	206,168	87	49	653.8
C	42,500	0.102	530,340	269,563	94	33	0
D	151,00	0.119	620,066	293,129		27	5,200
E	158,500	0.123	642,623	299,053		26	3,204
"Selling electricity back" scenario							
Scenario	Initial investment	COE	NPC	Electricity purchased	Fuel kg/year	Renewable coverage	Excess electricity
A	0	0.040	208,185			0	/
B	7,500	0.041	212,276	358,801	31	11	/
C	352,500	0.032	215,028	135,064	94	74	946,4

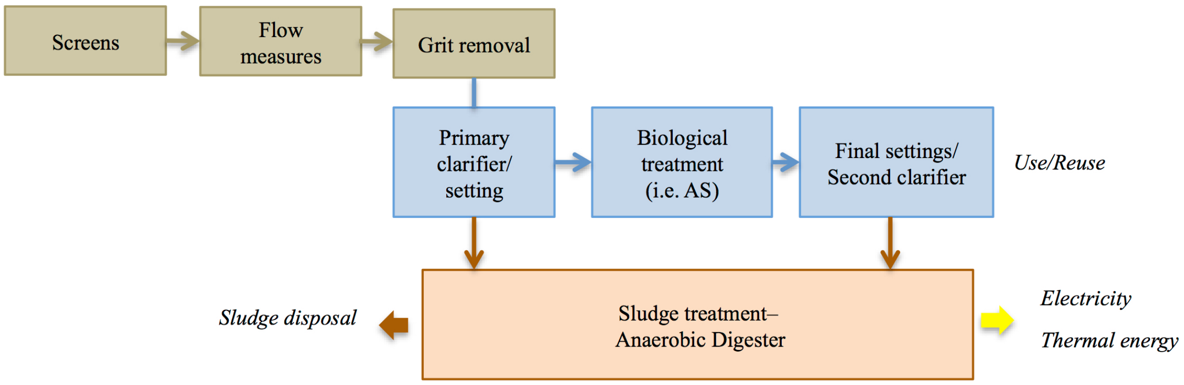
Table 7. Simulation results in three scenarios for a wastewater treatment facility with a Microbial Bioreactor system (Nominal power, working hours and electricity production of micro-generation technologies)

Baseline scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries Capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
0.04$/kWh										
A										
B		5			8,760			43,800		
C	5			4,469			11,531			
0.08$/kWh										
A		15			8,760			131,337		
B	5	15		4,469	8,760		11,531	131,316		
C		15	10		8,760	4,698		131,271	2,656	
D	5	15	10	4,469	8,760	4,698	11,531	131,240	2,656	
0.016 $/kWh										
A	120	15		4,469	8,760		276,735	131,400		
B	120	15	10	4,469	8,760	4,698	276,735	131,400	2,656	
C		15			8,760			131,400		
D		15	10		8,760	4,698		131,400	2,656	
E	120			4,469			276,735			
F	120		10	4,469		4,698			2,656	
G	120	15		4,469	8,760		276,735	131,400		350
Emergency scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries Capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
A	120	15		4469	8,760		276,735	131,400		
B	120	15	10	4469	8,760	4689	276,735	131,400	2,656	
C		15			8,760			131,400		
D	120	15		4469	8,760		276,735	131,400		350
E	120	15	10	4469	8,760	4689	276,735	131,400	2,656	
“Selling electricity back” scenario										
Solutions	*Nominal Power [kW]*			*Working hours*			*Production (kWh/year)*			*Batteries Capacity [Ah]*
	PV	ICE	Wind	PV	ICE	Wind	PV	ICE	Wind	
A										
B		5			8,760			43,800		
C	5	/	/	4,469			11,531			

Table 8. Simulation results in three scenarios for a wastewater treatment facility with a Microbial Bioreactor system (Economic results, electricity purchased, biogas consumption, renewable fraction, excess electricity)

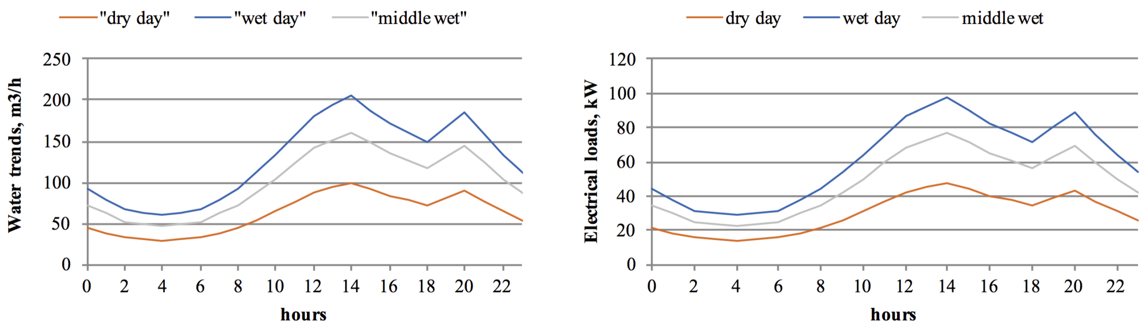
Baseline scenario							
Solutions	*Initial investment [$]*	*COE [$]*	*NPC [k$]*	*Electricity purchased [MWh]*	*Biogas [kg/year]*	*Renewable fraction [%]*	*Excess electricity [kWh]*
0.04$/kWh							
A	0	0.040	1,523	2,945			
B	7,500	0.040	1,527	2,902	31	1	
C	14,000	0.040	1,533	2,935		0.4	
0.08$/kWh							
A	22,500	0.079	2,991	2,815	94	4	
B	36,500	0.079	2,995	2,804	94	5	
C	42,500	0.079	3,016	2,811	94	5	
D	56,500	0.079	3,020	2,801	94	5	
0.016$/kWh							
A	352,500	0.151	5,744	2,566	94	13	946
B	372,500	0.151	5,766	2,563	94	13	946
C	22,500	0.155	5,901	2,814	94	4	
D	42,500	0.156	5,924	2,811	94	5	
E	330,500	0.156	5,935	2,697		8	946
F	350,500	0.156	5,958	2,695		9	946
G	457,500	0.157	5,974	2,566	94	13	946
Emergency scenario							
Solutions	*Initial investment [$]*	*COE [$]*	*NPC [$]*	*Electricity purchased [kWh]*	*Biogas [kg/year]*	*Renewable fraction [%]*	*Excess electricity [kWh]*
A	352,500	0.099	3,778	2,945	94	13	964.4
B	372,500	0.100	3,799	2,563	94	13	964.4
C	22,500	0.102	3,892	2,814	94	3	
D	456,000	0.105	4,003	2,567	94	13	1,646
E	476,000	0.106	4,024	2,564	94	13	1,646
"Selling electricity back" scenario							
Solutions	*Initial investment [$]*	*COE [$]*	*NPC [$]*	*Electricity purchased [kWh]*	*Biogas [kg/year]*	*Renewable fraction [%]*	*Excess electricity [kWh]*
A	0	0.040	1,523	2,945			
B	7,500	0.040	1,527	2,902	31	1	
C	14,000	0.040	1,533	2,935		0.4	

Figure 1



Screens
Flow measures
Grit removal
Primary clarifier/ setting
Biological treatment (i.e. AS)
Final settings/ Second clarifier
Use/Reuse
Sludge disposal
Sludge treatment– Anaerobic Digester
Electricity
Thermal energy

Figure 2



"dry day"
"wet day"
"middle wet"
Water trends, m3/h
250
200
150
100
50
0
0 2 4 6 8 10 12 14 16 18 20 22
hours
dry day
wet day
middle wet
Electrical loads, kW
120
100
80
60
40
20
0
0 2 4 6 8 10 12 14 16 18 20 22
hours

a) b)

Figure 3

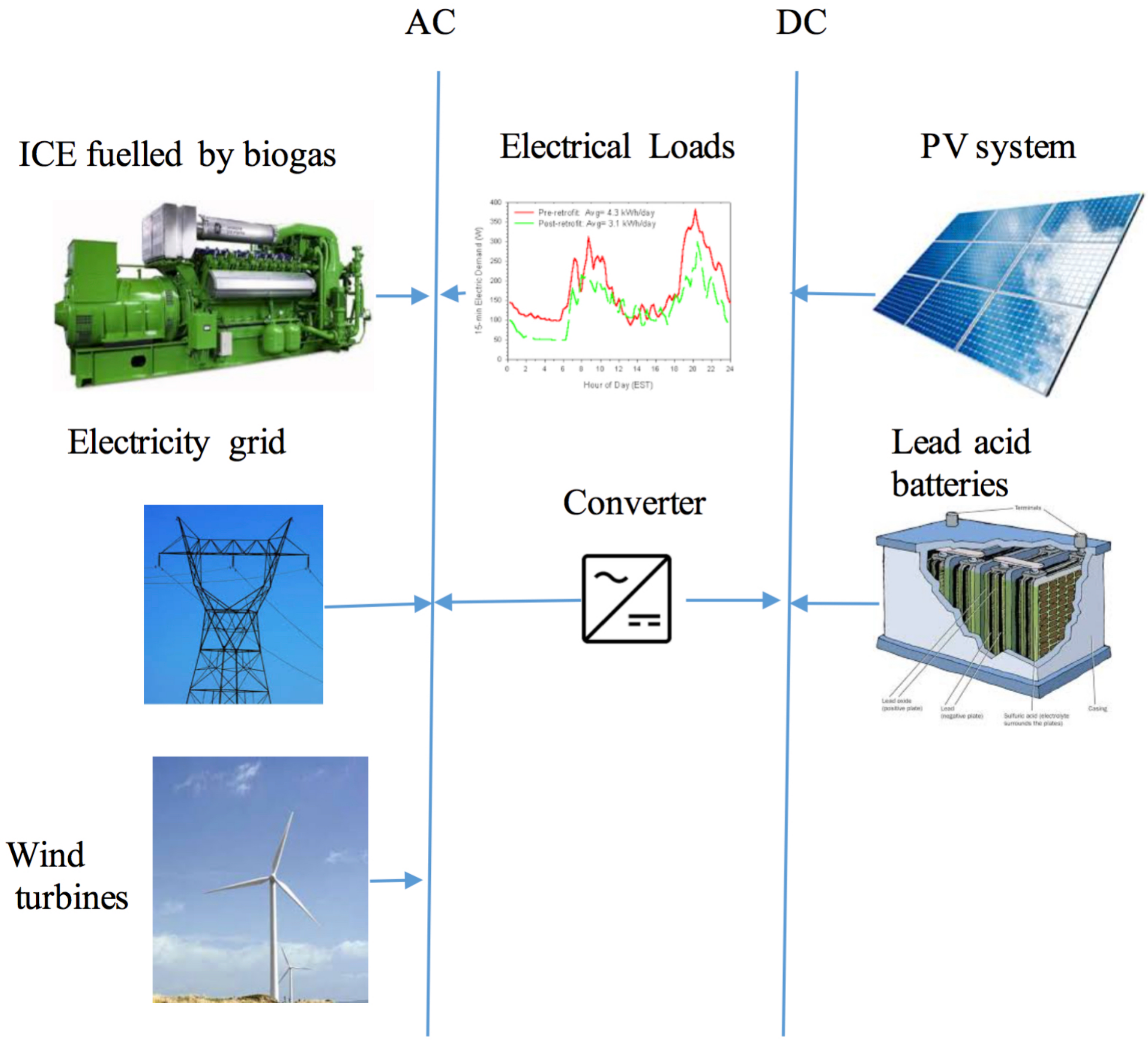

AC
DC
ICE fuelled by biogas
Electrical Loads
PV system
Electricity grid
Lead acid
batteries
Converter
Wind
turbines

Figure 4

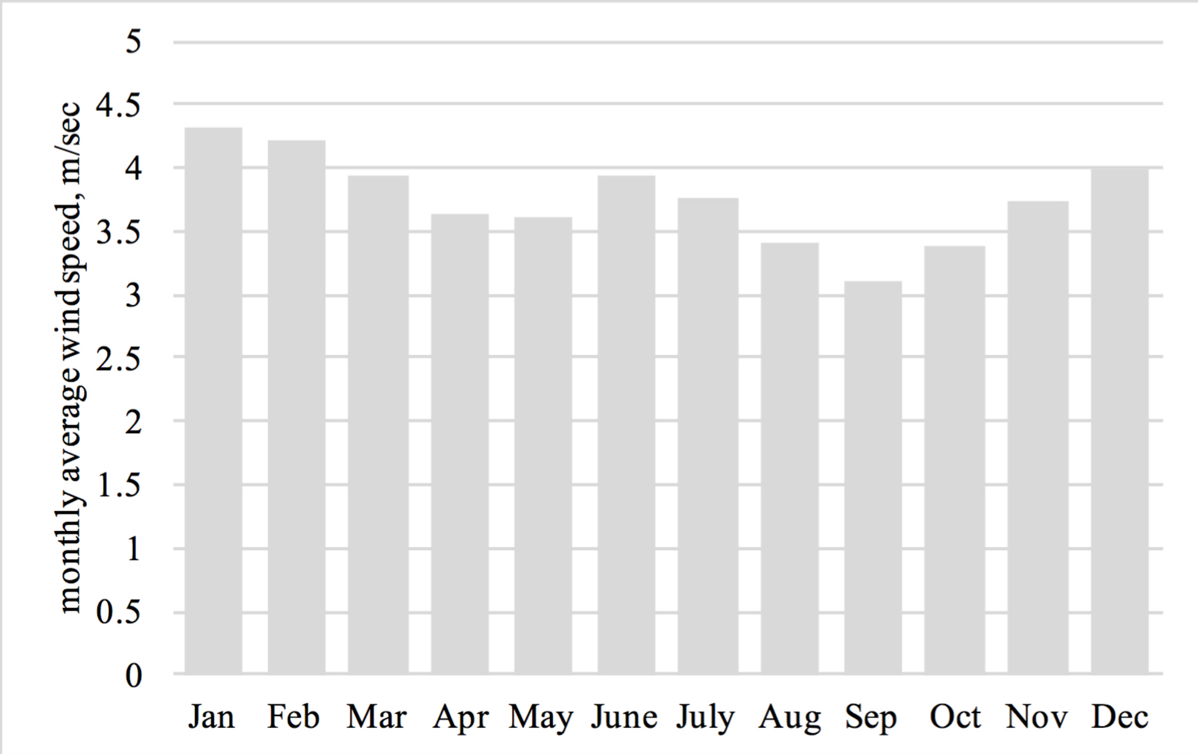
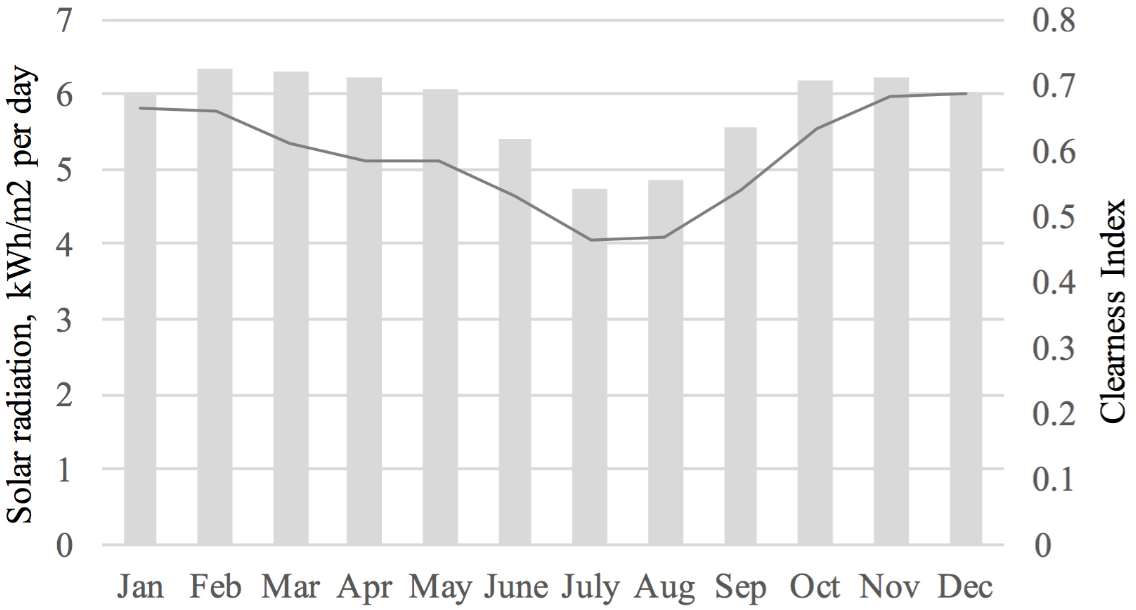

monthly average wind speed, m/sec
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 5



Solar radiation, kWh/m2 per day
Clearness Index
7
6
5
4
3
2
1
0
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec

Figure 6

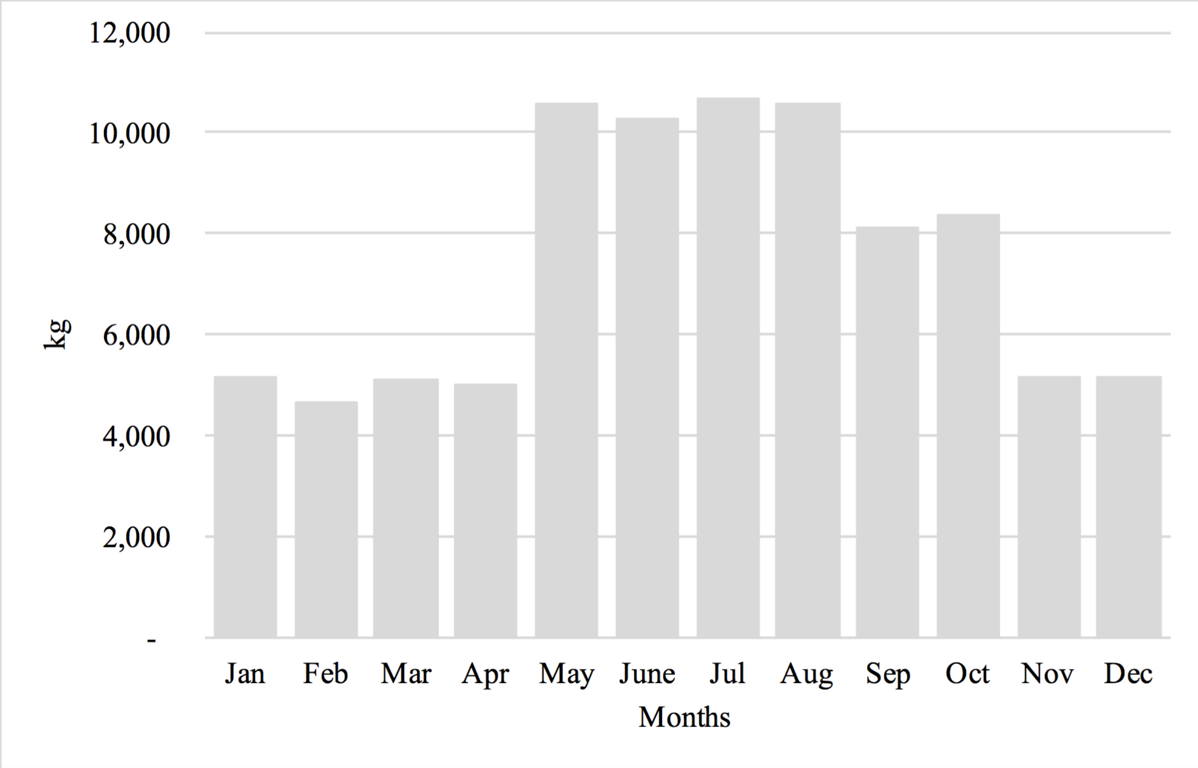
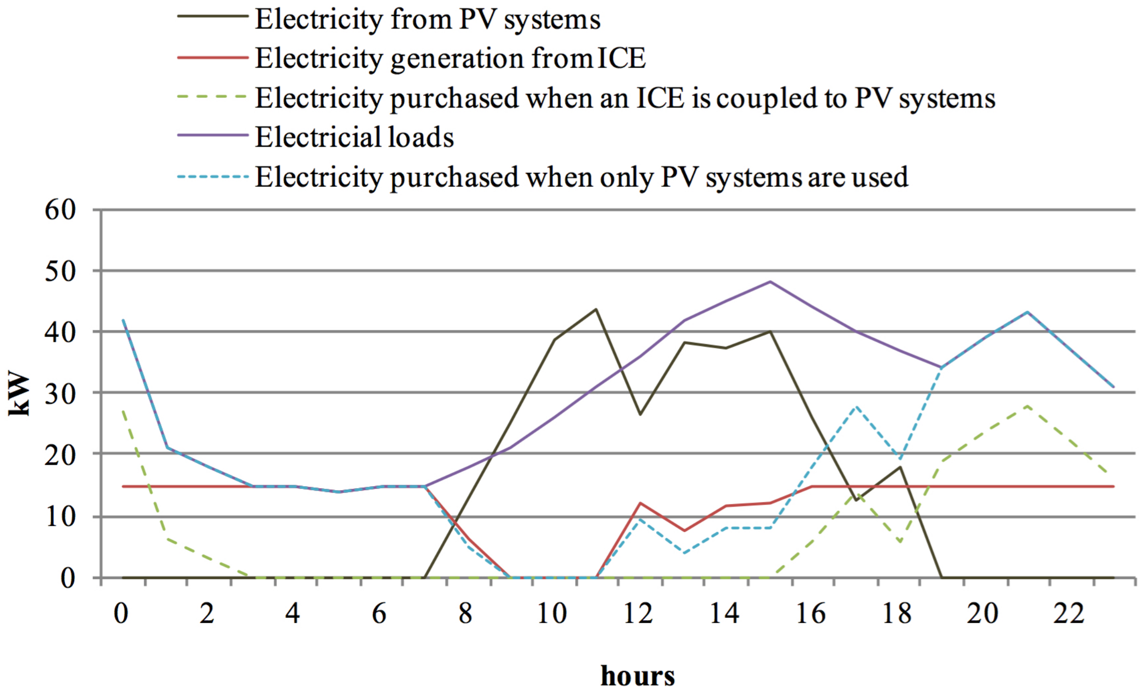

12,000
10,000
8,000
6,000
4,000
2,000
-
kg
Jan
Feb
Mar
Apr
May
June
Jul
Aug
Sep
Oct
Nov
Dec
Months

Figure 7


Electricity from PV systems
Electricity generation from ICE
Electricity purchased when an ICE is coupled to PV systems
Electricial loads
Electricity purchased when only PV systems are used
kW
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
hours