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Potential application of renewable energy sources at urban wastewater treatment facilities in Palestine – three case studies

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ABSTRACT

This paper aimed to assess the energy consumption and the removal efficiency of three wastewater treatment plants (WWTPs) in Palestine and explores the potential application of renewable energy with associated impacts on unit operations. National rules and regional guidelines for treated water are regulatory instruments for the construction approval of WWTPs in Palestine. Three urban WWTPs of various technologies were selected as case studies for the assessment. The technologies applied were conventional activated sludge with anaerobic sludge digestion, extended aeration and membrane bioreactor (MBR) serving Nablus, Al-Bireh and Altira cities, respectively. Analysis of collected data on the BOD_5 removal were 96%, 98% and 99%. The removal efficiency of nitrogen reached 85% and 95% for Al-Bireh and Altira and not accounted for in Nablus WWTP. The energy required for both liquid and sludge lines was calculated based on the available data and correlated with the treatment efficacy. Results analysis revealed wide variations in the energy consumption among the three WWTPs. Altira MBR showed normal trends compared to published literature with 2.88 kWh/m^3, of which 40% was consumed by the biological treatment stage. Al-Bireh WWTP consumed 1.86 kWh/m^3 with 35% of the electrical consumption for biological stage, and 24% for the sludge line. Nablus-WWTP consumed 2.25 kWh/m^3 with 62% of the energy consumed by the biological stage and 34% for sludge line. Under load operation below the design capacities, the specific energy consumption for Al-Bireh and Nablus WWTPs are contradicting common published data for activated sludge treatment systems. Use of renewable energy could assist in the reduction of the annual energy operational costs. Assessment of solar photovoltaic (PV) application could yield electricity sufficient for Altira and Al-Bireh pump station facilities covering 9%, 15%, and 1% of their energy demand. PV installation at Nablus WWTP showed marginal impacts if connected off-grid or if combined heat and power are not operational until 2020, payback periods were estimated at 7.5 and 18.7 years, respectively.

Keywords: Wastewater treatment; Removal efficiency; Treatment cost; Renewable energy

1. Introduction

Raw and partially treated wastewater is discharged into open valleys that pass through agricultural lands and aquifer recharge areas. The construction and operation of centralized wastewater treatment plants (WWTP) in Palestine is crucial for the protection of public and environment. However, the construction of WWTP faces financial, institutional and socio-political challenges. The latter entails stringent Israeli rules for the technical approval and construction permits issuance. Nonetheless, most of the WWTPs in the West Bank are located close to hydrological sensitive areas. Three major urban WWTPs serving Al-Bireh, Altira and Nablus are located on the eastern aquifer, western aquifer and upstream of surface water runoffs and freshwater springs, respectively. Hence, the approval for construction and operation of Palestinian WWTPs is governed by Article 40 of Oslo Accord; the interim water treaty between Palestine and Israel [1].

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The selection of treatment technology depends on wastewater characteristics and the treatment objectives as translated into desired effluent quality. The latter depends on the expected use of reclaimed water and potential impacts on the receiving water bodies. Control of the effluent quality is typically aimed to protect the public health (for recreation, irrigation, water supply), preservation of the oxygen content in the water, and prevention of eutrophication [2]. Beside the technical issues, treatment technologies encounter also the socio-economic and environmental aspects of the served communities to ensure sustainable development [3,4]. Different studies [5,6] reported that the activated sludge (AS) process is common biological treatment method used, however with considerable amounts of waste sludge generation [7].

Sludge treatment is an essential part of treatment in order to safely dispose it to environment, although the processing, reuse, and disposal of sludge is the most complex issue face the design- due to its offensive characteristics [6] after removing the offensive odor, destruction of pathogens, and partial destruction of sludge solids [6,8–11].

The type of sludge produced depends on a number of factors, such as the type of sludge separation and treatment processes employed, which is a function of the size of the treatment plant and wastewater characteristics [6]. Selection of best sludge stabilization process is dependent on the final requirements where comparison of volatile solids reduction, biological oxygen demand (BOD) concentration in the supernatant, use of final bio solids (fertilizers or to landfill), capital cost, and operation capacity between aerobic and anaerobic processes [6,8–10]. Noting that sludge digestion leads to the lowest economic and environmental impacts due to its volume being significantly reduced [12]. Efficiency of anaerobic sludge digestion is low compared to the aerobic digestion, even both are slow due to cell decay rate [7].However to increase the hydrolysis process and increase the gas production, different pretreatment methods are used as alkalinity, thermal, thermalalkaline, ultrasonic, and ozone-oxidizing [13]. However there is few data upon comparison between aerobic and anaerobic sludge digestion after pretreatment [6].

Compared to aerobic sludge stabilization, the anaerobic sludge digestion is applied urban WWTPs due to long sludge retention time and biogas production, however, higher capital expenditures and operation staff with high skills are required. Researchers reported that the aerobic digestion is most effective at design capacities of 20,000 m^3/d [8], 19,000 m^3/d [14], and 18,900 m^3/d [3]. Furthermore, aerobic sludge digestion is more adequate for small scale WWTPs due to short retention time although higher energy demand is required [15]. On the other hand, WWTP with no biogas utilization anaerobic sludge digestion is unsustainable; biogas is flared to reduce the plant carbon footprint [16]. Considering stringent regional effluent consents, local environmental, economical, and socio-political considerations, membrane bioreactors (MBRs) are considered as the most favorable treatment technology option for wastewater treatment and reuse [17].

This study aims at exploring the application potential of renewable energy to efficiently operate the WWTPs of Nablus, Al-Bireh and Altira. The study highlights the sustainability of renewable energy implementation at Nablus WWTP and provides comparative analysis among the three WWTPs pertinent to operational costs, efficiency, effluent quality, and energy demand. Finally, the renewable energy required to support the major mechanical facilities at each WWTP is assessed.

2. Energy requirements for operating wastewater treatment plants

Estimates show that the electrical energy to operate wastewater treatment is about 3–5% of the electrical load in many developed and developing countries [18]. Considering the continuous rise in energy costs [19], reducing energy load is not only correlated to reducing the WWTP carbon footprint but also considered of great economic impact [19].

Energy requirement to run operation process differ according to the technology, where for AS 0.24 kWh is required to treat 1 meter cube of wastewater, considering that 42% and 22% of energy consumption is required to run aeration and pumping respectively [20]. Considering the operational parameters, membrane types, treatment capacity and aeration systems of MBRs, the energy demand can vary between 5–6 kWh/m^3 [17]. Hence, compared to conventional AS, the overall energy consumption of municipal MBRs can reach two to four times higher [21].

Efficient operation of a WWTP can be achieved through improving efficiency of the operating units, and utilization of the green energy [7]. Utilizing green energy resources tailored to specific site conditions is necessary to improve the energy independence in WWTPs [20], utilization of solar energy and other mechanical renewable energy sources are not governed by the sludge treatment process [22]. Furthermore, the International Energy Agency (IEA) underlined the importance of energy efficiency, cleaner use of fossil fuel, capture and storage of carbon, utilization of renewable energy [23]. The feasibility of methane production from anaerobic sludge digestion, solar and wind energy was also explored in other studies [14].

According to the IEA fact sheet [23], methane is the second largest anthropogenic green house gas (GHG) behind carbon dioxide (CO_2), but is over 20 times more effective than CO_2 at trapping heat in the atmosphere. Methane production in WWTP contributes to 5% of the global methane emission [24]; El Fadel and Massoud [25] recognized the use of anaerobic digestion in developing countries for biogas recovery to reduce methane emissions.

Cakir and Stenstorm [26] stated that techniques to capture methane and utilize it as fuel gas would make the anaerobic treatment preferable combination to very low influent strength. They also correlated the biological loading rate where in wastewater influent above 700 mg/L BOD anaerobic digestion turns feasible as the system will be producing negative CO_2 due to biogas combustion and utilization [26]. According to Tyagi and Lo [27] similar output regarding capturing of methane and utilizing it to generate electricity replacing of fossil fuels were reported.

It worth mentioning that reusing of biogas produced during wastewater treatment might compensate the WWTP capital and operational costs [18]. And the WWTP could be a net energy producer when employing the combined heat and power (CHP) as it provide adequate energy conversion efficiency [18].

Regarding solar energy utilization, few papers discussed [28], nor adequately investigated its application, mentioning that Han, et al. has studied the solar energy utilization for a small scale plant and found that the dispersion of the plant component makes it feasible to utilize solar energy [28].

In Palestine solar photovoltaic (PV) application is encouraged due to the high potential solar energy, where the sun hours exceed 3,000 h/y with average penetration factor 5.4 kW/m^2 [29,30], the solar energy production premaster plan emphasized that the solar energy projects is highly encouraged by the Palestinian Energy Authority [31] as an adequate, sustainable, cost effective alternative source of energy in addition to environmental friendly reducing the GHG emissions [31,32]. In addition to that utilizing of PV systems for electrification of rural and remote villages in Palestine is economically profitable [32,33] whereas per Judi et al. the energy production of solar PV in Palestine reached 7.24% of the country energy balance [32].

3. Materials and methods

To achieve the study main objective, a comprehensive of and tedious long process in data collection has been conducted. This included a detailed literature review, technical field visits to the three WWTPs and personal communications with different key staff in the Palestinian Water Authority (PWA) [34], Nablus WWTP, Al-Bireh Wastewater Department, and AltiraMBR operating contractor. Relevant chapters in handbooks and many scientific articles published in refereed journals pertinent to wastewater treatment technologies were analyzed. In addition, available and accessible technical, economical and operational data were critically analyzed and evaluated. Verifying the data made available revealed a lack and confidentiality of databases inspected, which forms a major challenge during the study progress.

3.1. Description of three urban WWTPs as case studies

The Palestinian WWTPs planning, design and operation are governed by site specific requirements, socio-economic, environmental considerations and face special constrains related to institutional and funding agencies. All of that affect the type of technology applied [34]. For the purpose of this study, three case studies comprising Nablus WWTP (KfW German funding), Al-Bireh WWTP (KfW German funding), and Altira MBR (public owned and financed) are selected.

Nablus WWTP: The technical design and implementation was put on hold for more than a decade due to Israeli restrictions [35]. The WWTP is designed to serve 300,000 residents of western area of Nablus city and nearby villages. The construction of the plant shall follow three stages, where the first stage is designed to serve 150,000 resident by 2020 with a treatment capacity of 14,869 m^3/d [36]. The effluent is expected to reach a quality of 20, 30 and 50 mg/L for BOD5, total suspended solids (TSS) and nitrate as nitrogen (NO_3-N); respectively [36].

The final design incorporated Conventional Activated Sludge technology with the option of the utilization of anaerobic digestion to produce energy from biogas [35,37]. However the feasibility of this option or even cost, operation costs are not verified, though it would be part of this study to ensure verification of this option in addition to another option incorporating PV as renewable energy supporting source [35].

The plant produce 2,900 m^3/d of Bio Gas 65% of it is CH_4, only 308 m^3/d is filtered and utilized into heat exchanger for the patented anaerobic digester, 60 m^3 of biogas is burned each 2.16 h (estimated) to maintain the gas volume in the balloon to maximum 90% of the balloon capacity [35–37].

Al-Bireh WWTP was selected for this study as an example of energy exhaustion [33,38], the WWTP is operating since year 2000 serving 50,000 citizens [39], Nonconventional Activated Sludge technology was selected in order to minimize environmental risk of wastewater impact on Wadi AlEin and Wadi AlQilt, in addition to utilize the effluent for agricultural uses [38].

Altira WWTP was selected for the study as an example of the nonconventional wastewater treatment technology of MBR was selected to produce Class A effluent to minimize impact on the surface and ground water resources of Ein Qenia, the WWTP serves 25,000 residents of Altira Neighbourhood of Ramallah [40–42].

Analyzed data from the WWTP included BOD_5, TSS, Total Nitrogen and control parameters, in addition to other operational parameters such as electricity consumption for each component in the WWTP; results are not shown due to space limitations. Table 1 illustrates the treatment efficiency of the three WWTPs, the rates verify how distinctive the selection of the case studies, where energy requirement as part of the operational cost is to be assessed for comparison, and renewable energy potential to operate mechanical parts, mainly the pumps will be assessed.

Table 1
Treatment efficiency of Nablus, Al-Bireh, and Altira WWTPs

WWTP	BOD_5 removal efficiency	Suspended solids removal efficiency	Total nitrogen removal efficiency
Nablus [35,36]	96%	95%	N/A
Al-Bireh [38–41]	98%	98%	85%
Altira [40,41]	99%	99%	95%

3.2. Economic analysis of renewable energy resources potential

Basic calculation themes were used for the economic analysis included estimation of the total costs according to the following equations [43]:

$$\text{Total Cost}(USD) = \text{Investment Cost} + \text{Operation and Maintenance Cost} + \text{Environment Cost} \quad (1)$$

$$\text{Annual Cash flow between options}(USD) = \text{Incremental Benifits} - \text{Incremental Cost} \quad (2)$$

$$Net\ Present\ Values(USD) = Discount\ of\ Annual\ Cash\ Flow \quad (3)$$

$$Simple\ payback\ period(USD) = \frac{Total\ Cost}{Revenue\ or\ saving\ per\ year} \quad (4)$$

where Investment cost inclusive of PV system cost, proposed (assumed) cost of the CHP [35,37]; Operation and maintenance costs include: labor, material, testing, maintenance and replacement of filters, invertors, and batteries, where a percentage was given according to previous studies and personal communication; Environment cost was estimated based on IEA and TU Delft estimations for each type of energy source [44,45].

The main assumptions made are the following:

- Land cost is assumed for each site based on the location.
- Cost of PV include (PV, invertors, DC charge controller, batteries for 6-h storage is assumed USD 2,000 [46].
- PV cost is given of 1,100 USD/kW 2016 when PV is connected to the grid [46].
- In case PV is connected to the grid, Net metering applied by Palestinian Renewable Energy Law where 0.03 USD of the unit cost is deducted for storing the produced energy in the network [47].
- 1 kWp PV require 10 m² [29].
- Manpower and materials are not considered in the calculation of operational cost of any of the plants as detailed data wasn't given during meetings with the different parities.
- Environmental cost or benefit was not added to the total cost calculations in Al-Bireh and Altira WWTP although it would assist in increasing the net present value.
- For Nablus, the CHP is not operating, and CH_4 is flared to CO_2 where each 1 m³ flared CH_4 produce 1.8 kg CO_2 [48]
- Electricity network produce 778, and 698 g/kW of CO_2 respectively [45] [39], the cost of the emissions is 0.13 Euro/kg [44].
- Life Cycle of Nablus systems comparison is selected 20 years, with discount rate 4%.
- Annual Cash flow for Nablus included Total Cost excluding Environmental Cost as the current situation increase the air pollution.

4. Results and discussion

In order to clearly illustrate the distinctive variation of the three WWTPs (Nablus, Al-Bireh and Altira), effluent quality is reviewed and compared (Figs. 1, 2). One major point to highlight was the nitrogen removal in Nablus WWTP, which was not monitored in the effluent during the first stage [35–37]. The conceptual design [49] took into consideration simultaneous nitrification and denitrification process in the biological reactors and reported a sludge retention time of 10 d (15°C) to ensure nitrogen removal.

Considering pathogenic indicators, both Al-Bireh and Altira WWTPs produced an effluent quality of class A

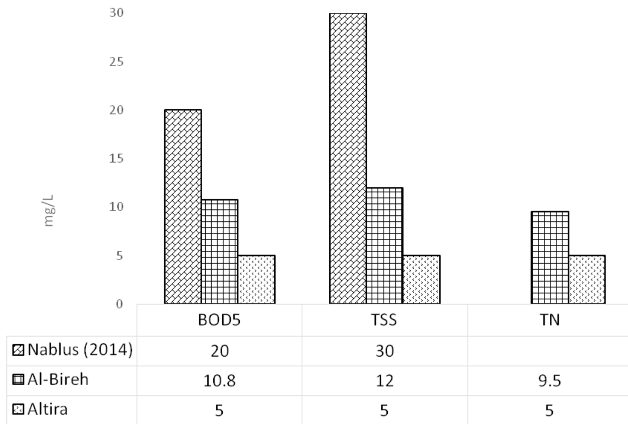

Fig. 1. Nablus, Al-Bireh and Altira WWTP effluent quality (BOD5, TSS, TN mg/L).

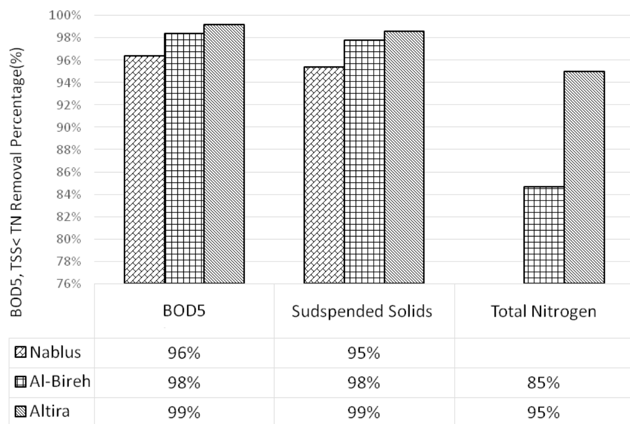

Fig. 2. Removal efficiency (%) of BOD_5, TSS, TN for Nablus, Al-Bireh and Altira WWTPs.

(results are not shown due to space limitations). This shows that aerobic sludge digestion in Al-Bireh WWTP and MBR installations together with aerobic sludge digestion in Altira MBR ensured a biologically safe reclaimed water. Since Nablus WWTP lacks a chlorinating system, the effluent complied with the minimal quality standards prescribed in the national effluent regulations issued by the Palestinian Standards Institution (PSI) [50].

Fig. 3 presents the relationship between effluent quality and the specific energy requirements to treat one cubic meter of wastewater (kWh/m³) for each WWTP. Altira MBR facility requires 2.18 kWh/m³ which is within the range reported by others [21].

On the contrary the estimated energy requirements for both conventional and extended aeration type of activated sludge systems serving Nablus and Al-Bireh cities was found to exceed published literature recommendations with (1.25 and 0.76 kWh/m³). It is worth mentioning that Nablus WWTP has a current operational capacity of only 75% of its design capacity in the initial planning phase. Though, in future, higher energy consumption is expected to achieve full nitrogen removal by 2020, however, operation under full capacity might reduce the specific energy

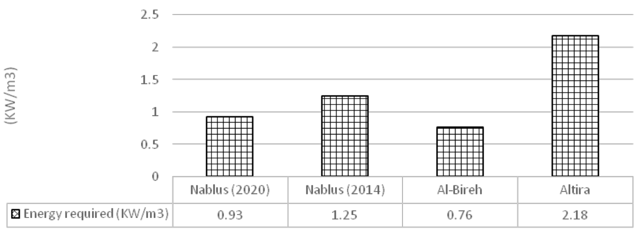

Fig. 3. Nablus, Al-Bireh and Altira WWTP energy consumed per treated cubic meter.

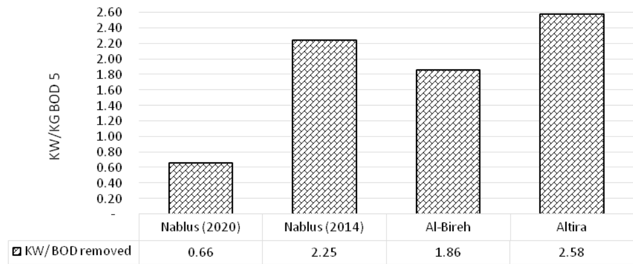

Fig. 4. Annual energy required to treat 1 kg of BOD5 in Nablus, Al-Bireh and Altira WWTP.

consumption down to 0.93 kW/m^3. Al-Bireh WWTP energy requirements is higher than literature, due to deficiency or accuracy of data or constrains related to the covered period (2004–2012).

Fig. 4 correlated the energy required to treat 1 kg $BOD_5$to less than 10 mg/L BOD_5, lower results estimated in Al-Bireh WWTP might be considered norm as the system is designed to treat nitrogen up to 85% [38,39], results for Altira WWTP is higher considering 95% nitrogen removal is achieved. Moreover, results could be correlated to BOD_5 removal efficiency of 96%, 98%, and 99% for Nablus, Al-Bireh and Altira WWTPs.

Furthermore and as results illustrated in Fig. 5, in order to verify how to step into renewable energy utilization, comparison among the three WWTPs with regards of percentage of energy required/utilized for the water treatment line and sludge treatment line. The values is estimated as percentage of the total annual energy cost; as per design for Nablus WWTP [35,36] design and operational data for Altira WWTP [40,42] and operational data for the year 2012 Al-Bireh WWTP [51]. The sludge line was excluded for Altira WWTP.

Results show that most of the energy is drawn in the secondary treatment; the estimate is considered high for Nablus WWTP even its conventional AS with 10 d sludge retention time; this output require further investigation. Sludge treatment in Nablus is expected to be higher as more units utilized to fulfil the operation of the anaerobic digestion.

Al-Bireh WWTP results shows that energy required to operate secondary and sludge lines are close due to the high energy demand to run the aerobic digestion and its components.

The anaerobic digestion sludge line in Nablus WWTP that consumes 34% of the total energy demand as anaerobic digestion line compared to the aerobic digestion sludge line that consumes 24% of total energy required to operate Al-Bireh WWTP.

4.1. The move to renewable energy

Considering the assumptions made earlier, calculations were made to assess the solar PV potentials in unit operations (pump stations), and revealed that it would cover about 9% and 15% of the energy demand, equivalent to 93 kWp for Al-Bireh and 202 kWp for Altira MBR facility. Options of setting Solar PV supporting units connected to the grid supported by net metering, or off-grid connected with battery saving for 6 h were investigated. The cost

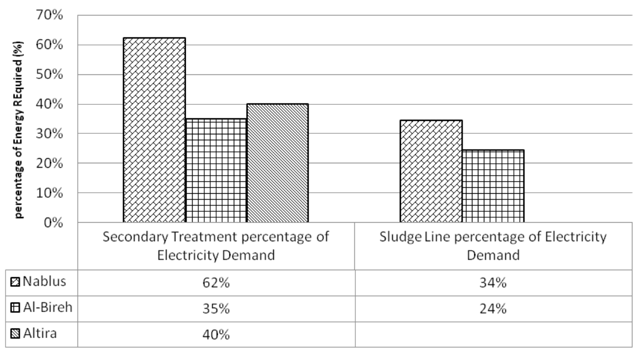

Fig. 5. Percentage of energy requirement for biological treatment and sludge line at Nablus, Al-Bireh and Altira WWTPs.

Table 2
Al-Bireh and Altira WWTPs via Solar PV replacement [Capacity and Cost Estimates]

WWTP	Solar power required (kW)	Solar PV connected to the grid cost estimate (USD)	Solar PV – off grid cost estimate (USD)
Al-Bireh	93	101,725.412	277,432.941
Altira	202	232,644.20	616,930.00

included the system components in addition to the land cost required for each system, the cost estimates are shown in Table 2. The simple payback period of the on-grid and off-grid PV systems were 3.7 and 8.0 years and results were similar for both WWTPs.

On the other hand, in Nablus WWTP percentage to operate pumping facilities didn't exceed 5%. Though the investigation was shifted to compare the cost estimates required for the following options: operate the anaerobic digestion where Burner only facilities the process- the current situation-, the on grid solar PV powered aerobic digestion, the off-grid solar PV with 6 h saving to power the aerobic digestion, and the option of operating the CHP.

The capital cost, annual savings, and simple payback were calculated. Figs. 6 and Fig. 7 illustrate the results. The results has shown that on grid connection is preferred considering the lowest capital cost, followed by

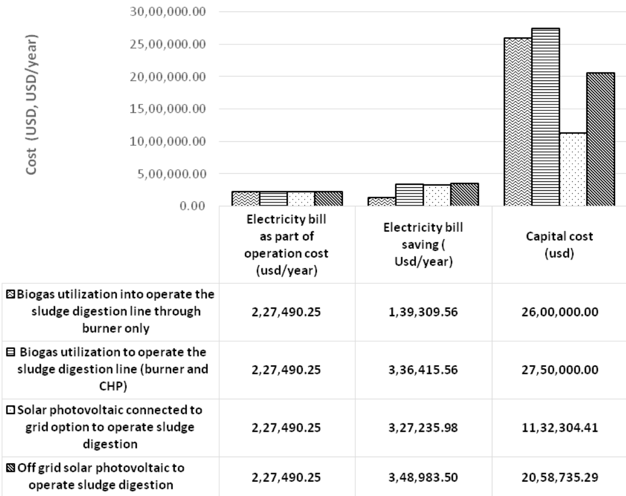

Fig. 6. Cost estimate and potential saving of renewable energy options Nablus WWTP.

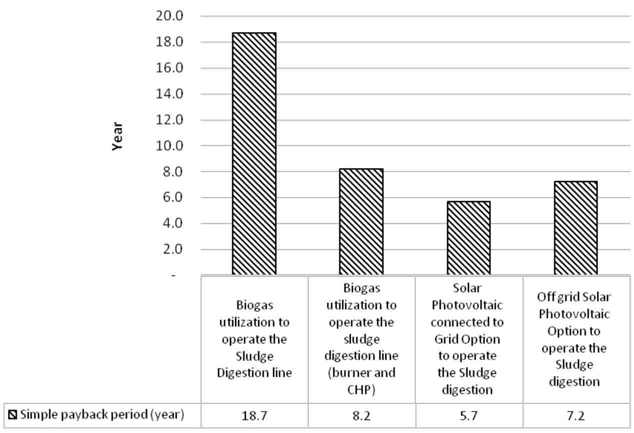

Fig. 7. Simple payback periods of the renewable energy options for Nablus WWTP.

the CHP as if operated will enhance the process. However, the off-grid solar PV will provide the better savings. On the other hand the existing situation assists on saving the electricity bill of the anaerobic digestion unit by almost 60%, yet if the system is kept being operated under the same conditions, the simple payback of the anaerobic digestion as renewable energy system will be 18.7 years as shown in Fig. 7.

Table 3 depicts the environment saving cost of the potential alternatives for renewable energy resources at Nablus WWTP. It is assumed that CH_4 is flared with no negative impacts due to CO_2 release to the atmosphere, the annual environmental costs for the current stage reached 131,133 USD and considered a loss of benefits.

Table 3
Environmental cost saving of investigated options for Nablus WWTP

Renewable energy option	Annual environmental cost savings (USD)
Biogas utilization to operate the sludge digestion line through burner only	–131,133
Biogas utilization to operate the sludge digestion line (burner and CHP)	340,251
Solar photovoltaic connected to grid option to operate the Sludge digestion	330,966
Off grid solar photovoltaic option to operate the Sludge digestion	389,372

5. Conclusions and recommendations

Introducing potential renewable energies to the wastewater treatment can be achieved in both liquid and sludge treatment lines. Reflecting this trend into the three WWTPs cases of Nablus, Al-Bireh and Altira MBR facility. Considering the technology type applied, installed unit operations, and treatment goals, the effluent quality can highly impact the specific energy consumption per treated cubic meter.

The specific energy consumption for biological wastewater treatment was estimated for each WWTP, where 2.18, 1.25, and 0.76 kWh/m^3 is required for Altira, Nablus (2014) and Al-Bireh WWTPs. The BOD_5 removal efficiency correlated with energy consumption with 2.58, 0.66, and 1.86 kWh/kg BOD_5 for Altira, Nablus (2014) and Al-Bireh WWTP. This was clearly reflected in higher BOD_5 removal efficiency of 99%, 96%, and 98%; respectively.

Power calculations to achieve tertiary treatment with aerobic or anaerobic sludge digestion were calculated with variations considering technology type. The anaerobic sludge digestion in Nablus WWTP consumed about 34% of the total energy demand compared with 24% for aerobic sludge digestion at Al-Bireh WWTP.

Application potentials of renewable energy was found through coupling for the operation of pumping facilities, especially during emergency conditions (power cut-offs). Solar PV's system could cover 15% and 9% of Altira and Al-Bireh WWTPs. Considering that similar energies were not studied for large plants as per stated in the overview, it's worth it to conduct further investigations, and look for governmental incentives for better net metering agreements.

Installations of PV systems (off-grid), capable to operate only in electricity outage situations, showed a payback period of 8 years. However, implementing this option might be considered as need to minimize the risk of plant failure to ensure a stable effluent quality for irrigation purposes.

The study gave insights into utilization of diverse renewable energy sources at Nablus WWTP, where currently no use of biogas and flared resulting in greenhouse gas emissions. The current operational phase consumed high energy demands, this calls for immediate CHP installations. CHP was suggested to biogas and energy recovery and save environment costs eliminating the energy dissipation reductions and the emitted CO_2minimization. Energy auditing studies at the three WWTPs warrant further studies to optimize energy consumption and reduce energy losses.

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