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Energy savings and reduced emissions in combined natural and engineered systems for wastewater treatment and reuse: the WWTP of Antiparos Island, Greece

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ABSTRACT

Europe's water service providers are under increasing pressure to deliver improved and affordable water services to a growing population, whilst reducing the amount of energy used, lowering the environmental impact of water and wastewater treatment processes, and coping with climate change. These challenges have prompted research on natural processes for wastewater treatment, such as constructed wetlands (CWs), providing low-energy treatment potential and storage capacity. As the performance of natural treatment processes may be limited by several factors (e.g. climatic conditions, space restrictions), considerable research concentrates on investigating their combination with engineered pre- or post-treatment processes to improve their performance and increase their treatment resilience. The aim of this paper is to assess and demonstrate the advantages of combined natural and engineered systems (cNES) over purely engineered treatment systems with regard to energy savings and reduced environmental impacts. The case of a cNES located in the island of Antiparos in Greece for the treatment and reuse of municipal effluents is investigated, focusing on the energy savings and the reduction of greenhouse gas (GHG) emissions from the natural treatment process. The performance of the system, which involves CWs for the secondary treatment of effluents, was assessed using an integrated modelling and simulation environment (baseline scenario). An alternative scenario was also built, substituting the CWs with a conventional activated sludge (CAS) process for the secondary treatment of effluents to achieve the same effluent quality as in the baseline scenario. Energy consumption and generation of GHG emissions was assessed for both scenarios, and a comparison between the two systems was conducted, highlighting the significant energy savings and the reduced GHG emissions produced by the cNES: the CAS system consumed about 3,000 times more energy, producing about 50 times more total GHG emissions compared with CWs. The results of the current analysis demonstrated that cNES involving CWs can provide a competitive alternative to purely engineered systems for wastewater treatment and reuse in isolated insular communities and small municipalities, also contributing to water scarcity reduction.

Keywords: Constructed wetlands; Activated sludge; Wastewater treatment and reuse; Energy savings; Greenhouse gas emissions; Antiparos Island

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1. Introduction

Europe's water service providers are under increasing pressure to deliver improved and affordable water services to a growing population, whilst reducing the amount of energy used, lowering the environmental impact of water and wastewater treatment processes, and coping with climate change [1]. These challenges have prompted water sector professionals to revisit the role of natural catchment landscape features, such as river banks, aquifers and wetlands, in providing low-energy treatment potential and storage capacity.

Research on the fundamental mechanisms and performance of natural processes for wastewater treatment, such as constructed wetlands and managed aquifer recharge systems, has advanced rapidly in recent years [e.g.: 2–4]. Natural treatment processes can provide cost-efficient and easily operated alternatives to purely engineered systems with many ecological and socio-economic advantages, e.g. lower operational costs and energy requirements, conservation of natural environment, zero visual obstruction [5,6]. However, the performance of natural treatment processes may be limited by several factors. Microbial degradation processes slow down at low temperatures; treatment performance for biodegradable compounds depends on the local climate and is affected by seasonal variations in temperature, especially low temperatures in winter [7]. In addition, the capacity of natural treatment processes may be limited due to space restrictions (e.g. size of constructed wetlands and infiltration basins) and long residence times, or negatively impacted by flow variations during floods and droughts. The combination of natural treatment processes with engineered pre- and post-treatment processes may help to overcome these limitations, improve performance and increase treatment resilience of natural processes. To this end, a considerable amount of research concentrates on investigating and assessing the potential advantages of combined natural and engineered treatment systems (cNES) over purely engineered treatment systems in delivering safe, reliable and efficient water services [e.g. 8–13].

The aim of this paper is to assess the advantages of using cNES for wastewater treatment and reuse, focusing on the energy savings and the reduction of greenhouse gas (GHG) emissions from the natural treatment processes involved. The case of the Antiparos wastewater treatment plant (WWTP) is investigated. An innovative WWTP / cNES was constructed in 2015 in Antiparos island, Greece, involving constructed wetlands (CWs) and a stabilization pond (for secondary treatment) with subsequent disinfection for the treatment and reuse of municipal effluents. The performance of the Antiparos cNES was assessed using an integrated modelling and simulation environment (baseline scenario), demonstrating the feasibility of CWs to obtain water suitable for irrigation of public spaces in isolated insular communities. An alternative scenario was then built for the island, substituting the CWs and the stabilization pond with an activated sludge process for the secondary treatment of effluents. The alternative scenario was designed to achieve the same effluent quality as in the baseline scenario. Energy consumption and generation of GHG emissions was assessed for both scenarios, and a comparison between the two systems was conducted, highlighting the significant savings and reduced emissions produced by the cNES.

2. Materials and methods

2.1. Study site area

Antiparos Island is part of the Cyclades complex, one of the Greek island groups that constitute the Aegean archipelago, located in the southeast Aegean Sea (Fig. 1). The island occupies an area of 35.1 km^2 and has a permanent population of 1,211 inhabitants (census 2011), while, during summer, about 1,000 seasonal residents and tourists visit the island (census 2012). Administratively, the island is part of the Regional Unit of Paros Island and it falls under the authority of the Municipality of Antiparos.

The island faces serious development issues, due to its isolated location and lack of infrastructure. Domestic wastewater in Antiparos was until recently disposed of through septic tanks, as there was neither sewage network nor central wastewater treatment in the island. The lack of a properly designed wastewater treatment system for the collection and treatment of the generated wastewater has caused significant problems in the island, especially during the summer period (rapid tourism development over the last 20 years), affecting both the natural environment (contamination of groundwater and marine environment), and the quality of life (generation of unpleasant odors, impacts on local economy).

The WWTP of Antiparos was constructed in May 2015, for the treatment and reuse of municipal wastewater, as part of the Regional Operational Programme of the South Aegean Region, which aims to improve the socio-economic development of the area and achieve the set national and European goals regarding environmental protection and resource efficiency [14]. It is located at Sifneikos Gyalos (500 m from the Antiparos settlement) and occupies an area of 28,400 m^2 (Fig. 2). The mean daily design capacity of the WWTP (for the year 2035) is 240 m^3 d^{-1} during winter (1,500 p.e.) and 480 m^3 d^{-1} during summer (3,000 p.e.) [15].

The influent to the Antiparos cNES undergoes pre-treatment (screening and grit removal), primary sedimentation (two parallel Imhoff tanks), secondary treatment (two stages of CWs of vertical subsurface flow beds planted with *Phragmites australis* plants: the first stage comprises four sealed beds with an area of 460 m^2 each, and the second stage comprises two sealed beds with an area of 750 m^2 each; the outflow of the second stage of CWs is collected in a sealed maturation pond with an average depth of 1.5 m), and

Fig. 1. Location of Antiparos Island, Greece.

disinfection (chlorination – dechlorination). Following the dechlorination stage, the treated wastewater passes through a well to yield samples and is then collected in a storage reservoir (volume: 220 m^3) and used for irrigation of public spaces located near the WWTP (restricted irrigation) (Fig. 3).

2.2. Adopted methodological approach

2.2.1. Modeling and assessment of the antiparos cNES performance (baseline scenario)

An integrated software modelling and simulation environment was used for the assessment of the performance of the Antiparos cNES. This modelling environment is an extension of the SEAT tool developed by Arampatzis et al. [16]. It assists in building the representation of a cNES by integrating libraries for the modeling of engineered and natural treatment processes and their interactions. This model forms the basis for evaluating the quantity and quality of wastewater, the generated sludge and emissions, the energy consumed and the chemicals used.

For the modeling and assessment of the Antiparos cNES the hydraulic and pollution loads entering the plant during the winter and summer periods were considered equal to those of the design study of the plant [15] (Table 1). The duration of the winter period was assumed to be eight months (245 d) and that of the summer period four months (120 d).

It was assumed that during the pre-treatment stage the amount of generated sludge equals to 0.03 L/m^3, while during the primary sedimentation 55% of the TSS and 35% of the BOD_5 are removed respectively. Model equations concerning the pollutant removal and the operation of CWs, the stabilization pond and the chlorination and dechlorination processes were found in the literature [17–19]. The model of Antiparos cNES, as developed in the integrated modeling environment is presented in Fig. 4.

The treatment performance of the cNES was assessed in both winter and summer conditions, through the estimation

Fig. 2. Location of the Antiparos WWTP (Source: Google Earth, 2018).

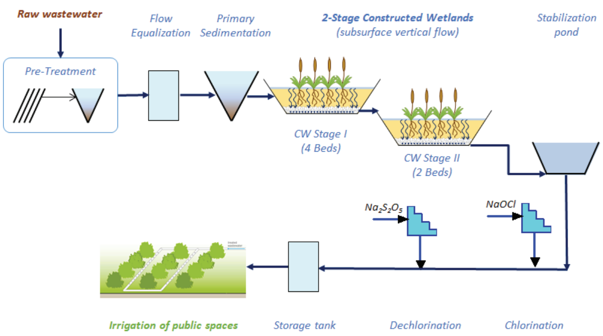

Fig. 3. Flow scheme of the Antiparos cNES.

Table 1
Hydraulic and pollution loads entering the antiparos cNES [15]

Parameter	Winter	Summer
Population equivalent (p.e.)	1,500	3,000
Mean daily flow, (m^3 d^{-1})	240	480
Max hourly flow, (m^3 h^{-1})	41	71
BOD_5, kg d^{-1} (mg L^{-1})	90 (375)	180 (375)
Total suspended solids (TSS), kg d^{-1} (mg L^{-1})	105 (438)	210 (438)
Total nitrogen (TN), kg d^{-1} (mg L^{-1})	18 (75)	36 (75)
Total phosphorus (TP), kg d^{-1} (mg L^{-1})	3 (13)	6 (13)
Escherichia coli (E. coli), #/100 mL	10,000,000	10,000,000
Wastewater temperature (T), ºC	14	22

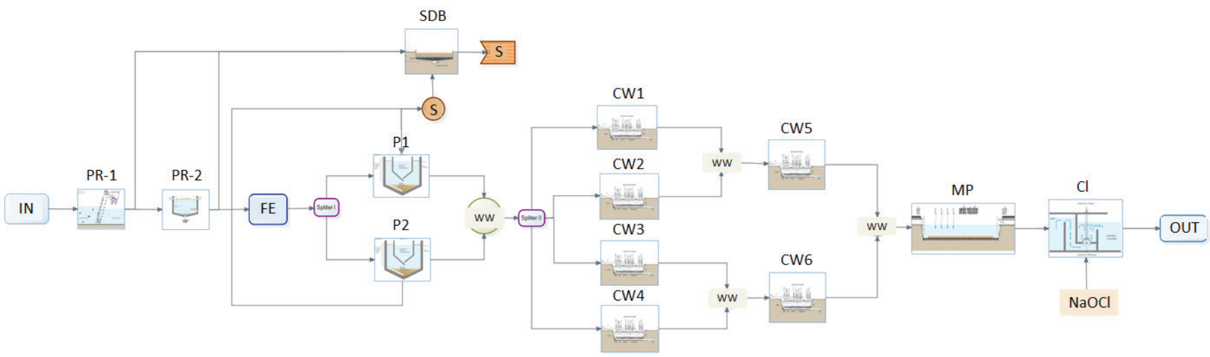

Fig. 4. Model of the Antiparos cNES (Baseline Scenario). IN: Influent; PR-1: Screening pre-treatment process; PR-2: Grit removal pre-treatment process; FE: Flow equalization tank; P1, P2: Imhoff tanks for primary sedimentation; CW1-6: Constructed wetland beds; MP: Maturation ponds; Cl: Chlorination; OUT: Effluent; S: Sludge; WW: Wastewater.

of the pollutant removal of each treatment process. The aim was for the system to achieve the required quality limits for the reuse of treated effluents for restricted irrigation, as specified by the Greek Water Reuse Legislation (CMD 145116/2011) (Table 2) [20].

2.2.2. Design of an activated sludge process for the antiparos WWTP (alternative scenario)

An alternative scenario substituting the CWs with a conventional activated sludge process (CAS) was developed. The CAS was designed to achieve the same effluent quality as the CWs (same concentrations of BOD_5, TSS and TN leaving the CAS system), following the methodology suggested by Dimopoulou [21], while the whole system was modelled to reach the same effluent quality at the outlet as in the baseline scenario (same concentrations of BOD_5, TSS, TN, TP, and E. coli in the treated effluents).

In the developed scenario the CAS system involves an anoxic tank for effluent nitrification/denitrification, an aeration tank (bioreactor used for the biological degradation; aeration source: submerged aeration diffusers/air blowers), and a secondary clarifier (settling tank where the mixed liquor solids are separated from the treated effluent; they are partially re-circulated to the aeration tank). The set parameters for the design of the CAS are presented in Table 3. The model of the Antiparos WWTP, having CAS instead of CWs and stabilization pond, as developed in the integrated modeling environment is presented in Fig. 5.

2.2.3. Calculation of energy consumption

The energy consumption of the Antiparos cNES (baseline scenario) for the first 30 months of plant operation was recorded by the electricity meter box of the plant (kWh).

For the alternative scenario, the energy consumption of the CAS was calculated following the approach proposed in the master thesis of Dimopoulou on the development of a theoretical model for the calculation of the energy consumption and of the generated GHG emissions by CAS based WWTPs [21]. The most energy-intensive parts of the CAS system are the aeration tank and the sludge treatment unit [21,22]. In the present study a conservative approach suggested by Dimopoulou's Scenario B was followed for estimating the energy consumption of a CAS system after primary sedimentation; only the energy consumption of the aeration tank was considered, taking into account the energy consumed for air pumping by the aeration system (energy consumption by mixing devices, pumps for mixed liquor recirculation, sedimentation scrappers etc., was not considered). The aeration flow requirement was estimated, and submerged aeration diffusers of suitable capacity were selected for the air diffusion in the aeration tank.

Table 2
Provisions of the Greek Water Reuse legislation for the reuse of treated effluents for restricted irrigation [20]

Potential use	Minimum required treatment level	Required quality limits
Agricultural use (restricted irrigation)	Secondary biological treatment and disinfection	E. coli ≤200 EC/100 mL (median) BOD_5 ≤25 mg L^{-1} TSS ≤35 mg L^{-1} TN ≤45 mg L^{-1}

Table 3
Biological kinetic parameters set for the design of the CAS system [21]

Parameter	Winter	Summer
Cell residence time in the aeration tank ($\theta_{C,A}$), d	10.00	5.00
Mixed liquor suspended solids (MLSS), mg L^{-1}	3,500.00	3,500.00
Dissolved oxygen (DO), mg L^{-1}	2.50	2.50
Maximum heterotrophic growth rate for T = 20°C ($\mu_{H,max,20}$), d^{-1}	7.00	7.00
Constant (k_H)	0.07	0.07
Monod saturation constant (K_{SH}), mg L^{-1}	120.00	120.00
Heterotrophic decay rate coefficient in endogenous respiration (b_H), d	0.06	0.06
Heterotrophic yield coefficient (Y_H), kgVSS/kgBOD_5	0.65	0.65
Maximum autotrophic growth rate for T = 20°C ($\mu_{N,max,20}$), d^{-1}	0.60	0.60
Constant (k_N)	0.12	0.12
Monod saturation constant (K_{SN}), mg L^{-1}	0.5	0.5
Monod half-saturation constant of DO (K_{DO}), mg L^{-1}	0.5	0.5
Autotrophic decay rate coefficient (b_N), d^{-1}	0.05	0.05
Autotrophic yield coefficient (Y_N), kgVSS/kgBOD_5	0.15	0.15
Percentage of inert suspended solids entering the biological reactor (α), kgSS/kgBOD_5	0.10	0.10
Percentage of inert suspended heterotrophic bacteria (β), kgSS/kgBOD_5	0.20	0.20
VSS/TSS ratio	0.70	0.70

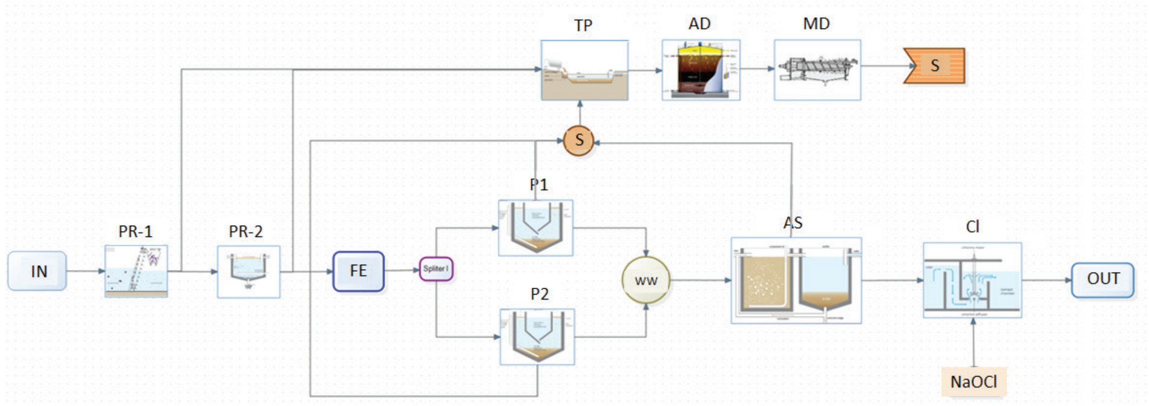

Fig. 5. Model of the Antiparos WWTP Involving a CAS System (Alternative Scenario). IN: Influent; PR-1: Screening pre-treatment process; PR-2: Grit removal pre-treatment process; FE: Flow equalization tank; P1, P2: Imhoff tanks for primary sedimentation; AS: Activated sludge process; TP: Thickening pond; AD: Anaerobic digestion; MD: Mechanical dewatering; Cl: Chlorination; OUT: Effluent; S: Sludge; WW: Wastewater.

For estimating the power requirements of the aeration system, the required daily air flow rate (Q_{AIR}) was calculated, using Eq. (1) [21]:

$$Q_{AIR} = \frac{R_{st}}{[O_2\%] \cdot d_{AIR} \cdot SOTE \cdot H_{\upsilon}} \quad (1)$$

where Q_{AIR} is required air flow rate (Nm^3 d^{-1}); R_{st} is required oxygen demand O_2 in standard conditions (kgO_2 d^{-1}); [O_2%]: oxygen percentage in the air; d_{AIR} is the air density in standard conditions (kg/m^3); H_{υ} is the aeration tank depth (m); SOTE is the specific oxygen transfer efficiency of diffusers under normal conditions per m of water depth (%).

The hourly Q_{AIR} was calculated by dividing the Q_{AIR} by 24, and the capacity and number of air blowers that should be in operation to meet requirements was selected based on this. Then, the absorbed blower power (P_W) of the selected aeration system was calculated using Eq. (2) [21]:

$$P_W = \frac{w \cdot R \cdot T_1}{29.7 \cdot n \cdot e} \cdot \left[\left(\frac{p_2}{p_1} \right)^{0.283} - 1 \right] \quad (2)$$

where P_W is the blower power absorbed (kW); w is the air mass flow rate (kg s^{-1}); R is the universal gas constant (8.314 kJ k mol^{-1} °K); T_1 is the air temperature at the inlet (°K); p_1 is the pressure at the inlet (atm); p_2 is the pressure at the outlet (atm); n is the constant; e is the blower aeration efficiency (%).

To calculate the daily energy consumption for wastewater aeration (kWh d^{-1}), the P_W was multiplied by the hours of operation per day and the number of operating blowers. The annual energy consumption was then calculated (kWh year^{-1}) based on the daily value.

2.2.4. Calculation of GHG emissions

Both direct/on-site GHG emissions (generated by the biological processes of the wastewater treatment facility) and in direct/off-site GHG emissions (generated by the production of the electricity consumed by the plant) were analysed. In both scenarios, the total GHG emissions generated were taken as the sum of the on-site and the off-site GHG emissions.

For the baseline scenario, the on-site GHG emissions generated by the CWs were calculated following the methodology proposed by the IPCC for CWs of vertical subsurface flow [23]. Methane (CH_4) and nitrous oxide (N_2O) emissions, produced in methanogenesis and nitrification/denitrification of N compounds by microorganisms respectively, were taken into account. CH_4 emissions depend on the organic material load in CWs, while N_2O emissions are calculated based on the total nitrogen load in CWs. CWs harvesting was assumed to have no impact on GHG emissions, as harvesting is performed rarely and the amount of harvested vegetation (quantity of harvested biomass) is generally very small. The total on-site GHG emissions generated by the CWs were calculated using Eq. (3):

$$GHG_{CWs} = \left(CH_4 Emissions \cdot GWP_{CH4} \right) + \left(N_2O\ Emissions_{CWs} \cdot GWP_{N2O} \right) \quad (3)$$

where GHG_{CWS} is the total on-site GHG emissions generated by the CWs (kg CO_2 e d^{-1}); CH_4 Emissions is CH_4 emissions from the CWs (kg CH_4 d^{-1}); GWP_{CH_4} is the global warming potential value for CH_4; N_2O $Emissions_{CWs}$ is the N_2O emissions from the CWs (kg N_2O d^{-1}); GWP_{N_2O} is the global warming potential value for N_2O

For the calculation of the CH_4 emissions generated by the CWs Eq. (4) was used [23]:

$$CH_4\ Emissions = \sum \left(TOW_j \cdot EF_j \right) \quad (4)$$

where CH_4 Emissions is CH_4 emissions generated by the CWs (kg CH_4 d^{-1}); TOW_j is the total organics entering the CWs (kg BOD d^{-1}); EF_j is emission factor (kg CH_4/kg BOD); j = number/type of CWs.

The emission factor for wastewater treatment using CWs was considered a function of the maximum CH_4 producing potential (B_o) and the methane correction factor (MCF):

$$EF_j = B_o \cdot MCF_j \tag{5}$$

where EF_j is the emission factor (kg CH_4/kg BOD); j is the number/type of CWs; B_o is the maximum CH_4 producing capacity (kg CH_4/kg BOD); MCF_j is the methane correction factor (fraction).

The MCF and B_o values proposed by the IPCC [23] for domestic wastewater entering the CWs of vertical subsurface flow were used.

Eq. (6) was used for the calculation of the N_2O emissions from the CWs [23]:

$$N_2O\ Emissions_{CWs} = \sum \left(N_j \cdot EF_j \cdot 44/28 \right) \tag{6}$$

where N_2O $Emissions_{CWs}$ is the N_2O emissions generated by the CWs (kg N_2O d^{-1}); N_j is the total nitrogen entering the CWs (kg N d^{-1}); EF_j is the emission factor (kg N_2O/kg N); j is the number/type of CWs; The factor 44/28 is the conversion of kg N_2O-N into kg N_2O.

The emission factor for N_2O emitted from domestic wastewater treated by CWs of vertical subsurface flow was considered equal to 0.00023 kg N_2O-N/kg N [23].

In this analysis the global warming potential (GWP) values relevant to CO_2 proposed in the latest report of the IPCC for the 100-year time horizon [24] were considered. These values, which were used for the calculation of GHG emissions in kg CO_2 equivalents for both scenarios, are presented in Table 4.

For the alternative scenario, the on-site GHG emissions generated by the CAS system were calculated following the methodology proposed by Dimopoulou [21]. CO_2 emissions from the biomass decay and oxidation as well as N_2O emissions from the denitrification processes were considered. The total on-site GHG emissions generated by the CAS system were calculated using Eq. (7):

$$GHG_{CAS} = CO_{2,\text{biomass decay}} + CO_{2,\text{BOD oxidation}} - CO_{2,\text{consumed}} + \left(N_2O\ Emissions_{CAS} \cdot GWP_{N_2O} \right) \tag{7}$$

where GHG_{CAS} is the total on-site GHG emissions generated by the CAS system (kg CO_2 e d^{-1}); $CO_{2,\text{ biomass decay}}$ is the CO_2 emissions from biomass decay through endogenous respiration (kg CO_2 d–1); $CO_{2,\text{ BOD oxidation}}$ is the CO_2 emissions from the oxidation of organic load (kg CO_2/d^{-1}); $CO_{2,\text{ consumed}}$ is the CO_2 consumed by bacteria (Nitrosomonas and Nitrobacter) for nitrification (kg CO_2 d^{-1}); N_2O $emissions_{cas}$ is the N_2O emissions from denitrification (kg N_2O d^{-1}); GWP_{N_2O} is the global warming potential value for N_2O

The CO_2 emissions generated by biomass decay through endogenous respiration were calculated using Eq. (8):

$$CO_{2,\text{biomass decay}} = X_{\text{decay}} \cdot 1.95 \tag{8}$$

The X_{decay} is the amount of decomposed biomass per day, and is considered a function of the daily influent flow rate, the sedimentation retention time, the concentration of volatile suspended solids in the mixed liquor and the heterotrophic decay rate coefficient in endogenous respiration. Further information for the calculation of X_{decay} is given in Dimopoulou [21]. According to the stoichiometry, 1kg $C_5H_7O_2N$ produces 1.95 kg CO_2, hence X_{decay} is multiplied by 1.95 to calculate the amount of CO_2 generated from biomass decay.

Table 4
GWP values for selected GHG [24]

GHG	Chemical formula	GWP values for 100-year time horizon
Carbon dioxide	CO_2	1
Methane	CH_4	28
Nitrous oxide	N_2O	265

The CO_2 emissions generated from the oxidation of organic load were calculated using Eq. (9):

$$CO_{2,\text{BOD oxidation}} = RO_2 \cdot 1.10 \tag{9}$$

The RO_2 is the oxygen requirement for biomass production through BOD oxidation, and is considered a function of the daily influent flow rate, the concentration of BOD_5 in the wastewater entering the system, the removal rate of organic load, the total solids residence time in the CAS system, the equivalent microorganism mass in ultimate BOD, the ratio of BOD_5 to ultimate BOD, the heterotrophic yield coefficient, and the heterotrophic decay rate coefficient. The RO_2 was calculated following the method suggested by Dimopoulou [21]. According to the organics' oxidation stoichiometry, for 1kg O_2 1.1 kg CO_2 are being produced, hence RO_2 is multiplied by 1.10 to calculate the amount of CO_2 generated from the oxidation of organic load.

The amount of CO_2 consumed by bacteria for nitrification was calculated using Eq. (10):

$$CO_{2,\text{consumed}} = N_{\text{nitro}} \cdot 4.49 \tag{10}$$

The N_{nitro} is the amount of N nitrified in the aeration tank, and is equal to the total N entering the aeration tank minus the amount of N absorbed during the synthesis of biomass, the amount of ammoniacal N (N-NH_4) leaving the system, the amount of the organic N leaving the system, and the amount of N removed with the excess sludge [21]. According to the nitrification stoichiometry, 4.49 kg of CO_2 are being consumed for 1 kg N being nitrified, hence N_{nitro} is multiplied by 4.49 to calculate the amount of CO_2 consumed from the nitrification process.

Eq. (11) was used for the calculation of the N_2O emissions from the CAS system [21]:

$$N_2O\ Emissions_{CAS} = Q \cdot TN_{in} \cdot 0.005 \tag{11}$$

where N_2O $Emissions_{CAS}$ is the N_2O emissions generated by the CAS system (kg N_2O d^{-1}); Q is the daily influent flowrate (l d^{-1}); TN_{in} is the concentration of total nitrogen in the daily flow rate (kg TN l^{-1}).

The conversion factor of N_2O into N during the denitrification process differs according to the WWTP.

In the present analysis it was considered that 0.005 kg N_2O are produced for each kg of TN entering the system.

For the calculation of the off-site emissions generated by electricity production, the fuel mixture for Greece was considered, as provided by the national electric power company (Public Power Corporation S.A. Hellas) [25]. The Greek fuel mixture, including the percentages of fuel used for the power generation consumed by the mainland and the islands of the country for the year 2017, is presented in Table 5. The corresponding GHG emission factors for each fuel source, as suggested by Shahabadi et al. [26] are also given in Table 5. In the present analysis, Antiparos island was considered to be part of the non-interconnected system (the island was very recently connected to the main electricity grid of the country). To calculate the off-site GHG emissions for both scenarios the amount of energy consumed was multiplied by the percentages of the fuel sources used for electricity production and the corresponding GHG emission factors for each fuel source.

3. Results

3.1. Treatment performance of the antiparos cNES (baseline scenario)

The treatment performance of the Antiparos cNES was assessed in both winter and summer conditions. The assessment results showed a significant reduction of BOD and TSS after CWs (about 96% and 98% respectively), while TN and TP were also removed by the CWs (about 77% and 14% respectively), proving the substantial contribution of the CWs in the treatment. The combination of the CWs with the stabilization pond (maturation pond) and disinfection results in pathogen elimination, improving significantly the quality of treated effluents (88% of pathogens were removed after CWs; 96% of pathogens entering the stabilization pond were removed). Hence, the limits of the Greek Reuse Legislation for restricted irrigation are met proving the reliable performance of the system (Figs. 6 and 7).

Table 5
Fuel mixture for Greece and GHG emission factors [25,26]

Production units and interconnections	Interconnected system (%)	Non-interconnected system (%)	GHG emission factor (g CO_2 e/kWh)
Lignite	30.85	0.00	877
Oil	0.00	82.39	604
Natural gas	31.01	0.00	353
Hydroelectric	6.51	0.00	0
Renewable	19.89	17.61	0
Interconnections	11.74	0.00	0
Total	100.00	100.00	–

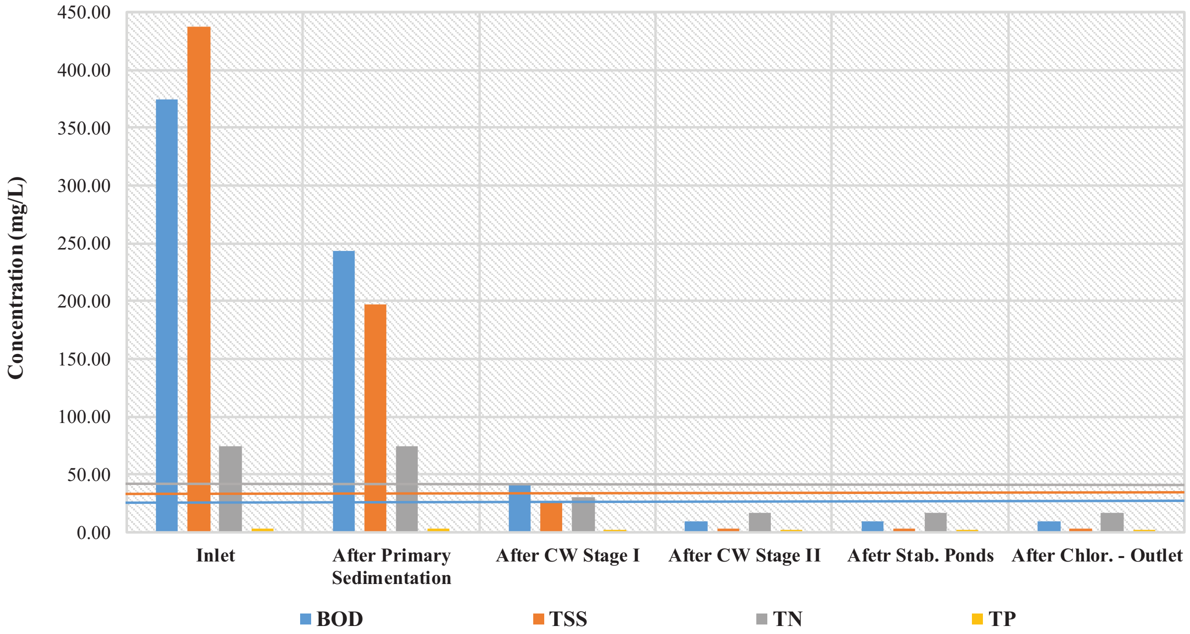

Fig. 6. Assessment results of pollutant removal in the Antiparos cNES for the summer period (the horizontal blue, orange and grey lines represent limits set by the Greek Reuse Legislation for restricted irrigation for BOD, TSS and TN respectively).

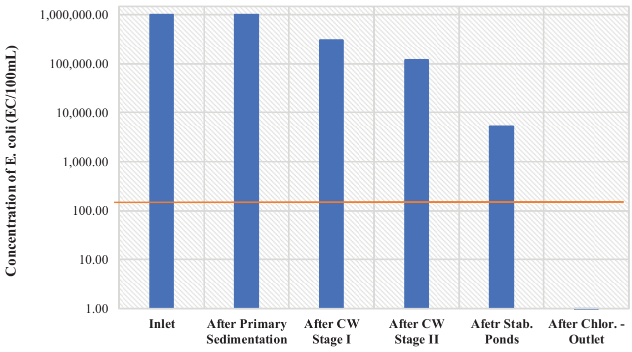

Fig. 7. Assessment results of E. coli removal in the Antiparos cNES for the summer period (the horizontal orange line represents limits set by the Greek Reuse Legislation for restricted irrigation).

3.2. CAS system for the antiparos WWTP (alternative scenario)

In the alternative scenario, a conventional engineered WWTP was modeled, including the same engineered processes with the cNES, but involving CAS for secondary treatment instead of CWs and maturation pond to achieve the same effluent quality (i.e. same concentrations of BOD_5, TSS and TN leaving the CAS system). The dimensions of the anoxic and aeration tanks of the CAS system, as well as the required air flow rate and the characteristics of the selected air blowers, as calculated by the model, are presented in Table 6.

3.3. Comparison of scenarios: energy consumption

The energy consumption of the Antiparos cNES for the first 30 months of plant operation, as recorded by the electricity meter box of the plant, was about 4,850 kWh. It was estimated that CWs contribute about 10% of the total energy consumption of the plant, due to the power needed for their feeding system (CW beds are flooded periodically through a piping system, and equal distribution of wastewater in the beds is achieved through a specially designed feeding system comprising storage tanks and mechanical doors which open automatically – electric valves – when the wastewater reaches a certain level). The daily energy consumption by the feeding system of CWs on a typical winter and summer day was estimated at about 0.40 and 0.80 kWh d^{-1} respectively, while the annual energy consumption for the operation of CWs was estimated at about 194 kWh y^{-1} (0.002 kWh/m^3).

The energy consumption of the CAS aeration unit was calculated taking into consideration the operation characteristics of Table 6. The daily energy consumption for wastewater aeration was estimated at about 1,560 kWh d^{-1} during winter and 3,045 kWh d^{-1} during summer, while the annual energy consumption of aeration was estimated at about 747,255 kWh y^{-1} (6.4 kWh/m^3). The CAS aeration requires constant electricity supply, and its energy consumption is significantly higher (about 3,000 times greater) compared with the consumption of CWs, as presented in Fig. 8.

3.4. Comparison of scenarios: GHG emissions

The total on-site GHG emissions generated by the CWs were estimated at about 15.50 kg CO_2 e/d in the winter period

Table 6
Design parameters of the anoxic and aeration tanks of the CAS system

Design parameter	Value
Anoxic tank volume V_{ANOX}, m^3	100
Aeration tank volume V_{AIR}, m^3	140
Total volume of biological processes V_{TOTAL}, m^3	240
Aeration tank depth H_u, m	3
Required air flow rate Q_{AIR}, $Nm^3 h^{-1}$	255 (winter) 464 (summer)
No. of air blowers in operation	1 (winter) 2 (summer)
Air blower capacity, $Nm^3 h^{-1}$	260
Blower power absorbed P_w, kW	66 (winter) 70 (summer)

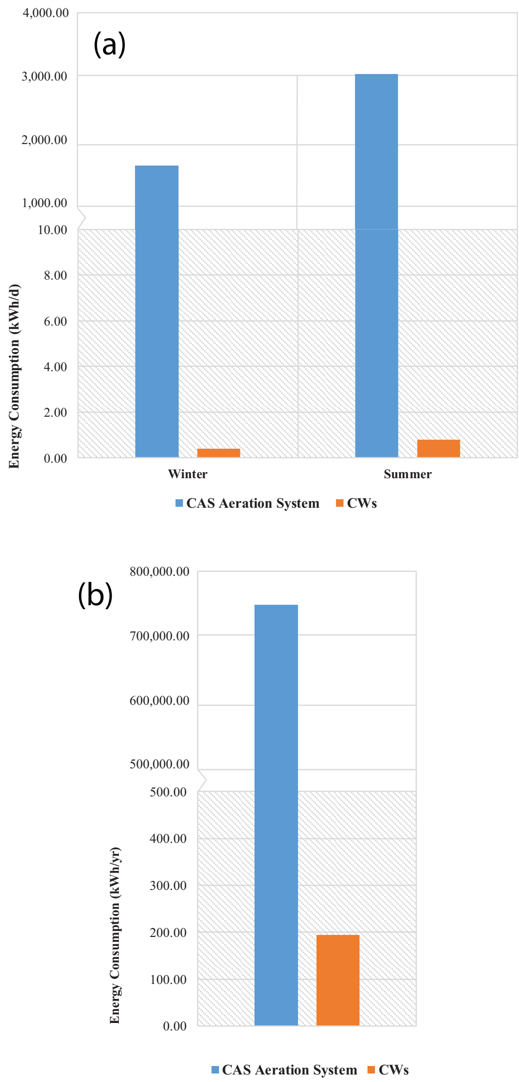

Fig. 8. (a) Estimated daily energy consumption of the CAS aeration system and the CWs during winter and summer; (b) Estimated annual energy consumption of the CAS aeration system and the CWs.

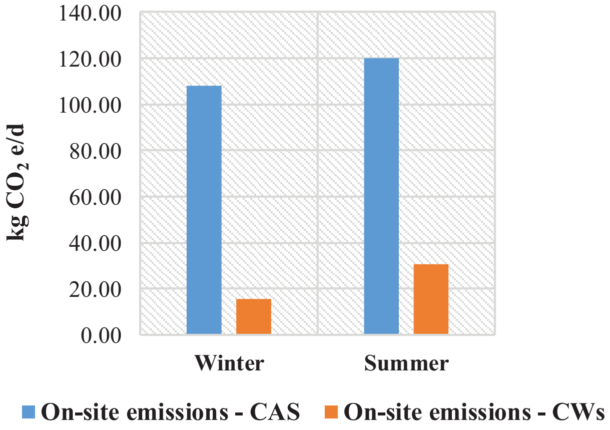

Fig. 9. On-site GHG emissions generated by the CAS and the CWs in the winter and the summer periods.

and 31.00 kg CO_2 e/d in the summer period. On a typical winter day 0.50 kg CH_4 are produced, while on a typical summer day 1 kg CH_4 are produced by the CWs. N_2O emissions during winter were estimated at about 0.01 kg d^{-1}; this amount is doubled during the summer period. The total off-site emissions generated by the electricity production for the operation of CWs were estimated at about 0.20 kg CO_2 e d^{-1} for winter days and 0.40 kg CO_2 e d^{-1} for summer days. Hence, the total GHG emissions produced by CWs in the winter and summer periods were estimated at about 15.70 and 31.40 kg CO_2 e d^{-1} respectively (0.07 kg CO_2 e/m^3).

For the alternative scenario, the on-site GHG emissions from biomass decay as well as from the oxidation and denitrification processes were estimated at about 108.00 kg CO_2 e d^{-1} on winter days and 120.00 kg CO_2 e d^{-1} on summer days. The total off-site emissions generated by the electricity production for the operation of the anoxic and aeration tanks of the CAS system were estimated at about 775.00 kg CO_2 e d^{-1} for a typical winter day and 1,515.00 kg CO_2 e d^{-1} for a typical summer day. Therefore, the total GHG emissions produced by the CAS in the winter and summer periods were estimated at about 883.00 and 1635.00 kg CO_2 e d^{-1} respectively (3.5 kg CO_2 e/m^3).

The total GHG emissions generated by the CAS system are about 50 times greater than those produced by the CWs. The off-site emissions, which depend on the energy consumed by each system, are the reason for this significant difference between the two systems (on-site emissions from CAS about 5 times greater than those from CWs; off-site emissions from CAS about 4,000 times greater than those from CWs). The on-site, off-site and total emissions produced by the two systems are presented in Fig. 9 and Fig. 10(a) and 10(b) respectively.

4. Discussion

According to the current analysis, CWs consume significantly lower amounts of energy generating correspondingly lower GHG emissions compared with CAS systems: the CAS system of the alternative scenario consumes about 6.4 kWh/m^3 producing 3.5 kg CO_2 e/m^3, while the CWs consumes about 0.002 kWh/m^3 producing 0.07 kg CO_2 e/m^3 to achieve the same

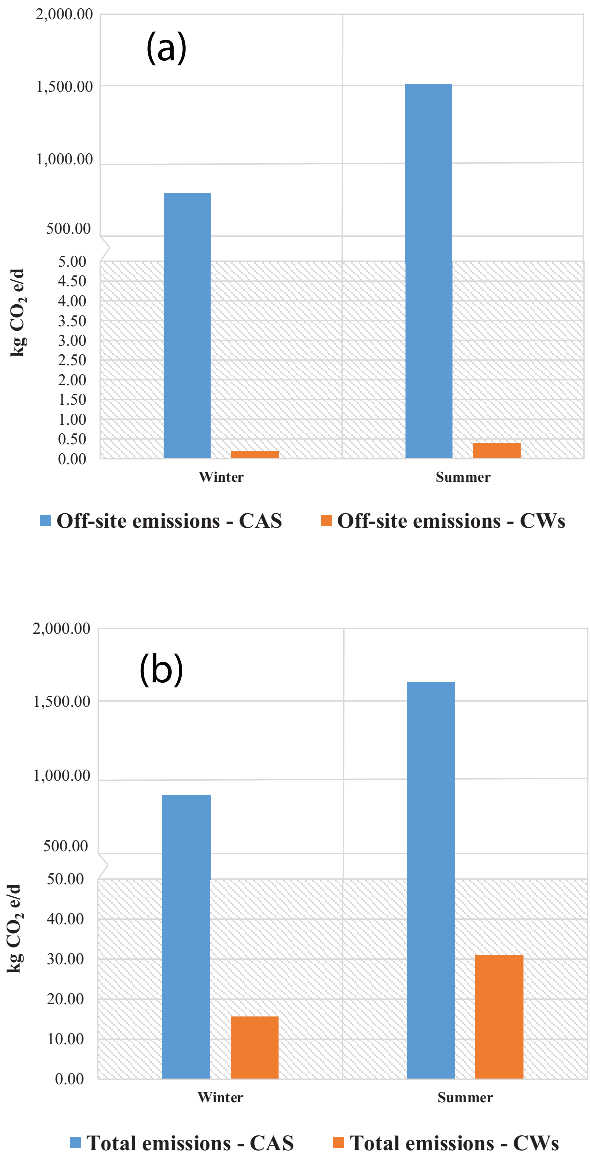

Fig. 10. (a) Off-site GHG emissions generated by the CAS and the CWs in the winter and the summer periods; (b) Total GHG emissions generated by the CAS and the CWs in the winter and the summer periods.

effluent quality. Similar results supporting the advantages of CWs over CAS for small communities (less than 2,000 p.e.) can be found in the literature. In the study of de Fingueiredo Simeão [29] the performance of twelve WWTPs serving small communities in Portugal by using CAS, lagoons and CWs, was evaluated and compared. The energy consumption of the CAS was significantly higher than the consumption of the CW systems. For example, the Alcoutin WWTP, using CAS to serve 340 inhabitants, consumed 3.02 kW/m^3 in 2011, which was about 27 times greater than the energy consumed by the Martinlongo WWTP, which was using CWs to serve 257 inhabitants and consumed 0.11 kW/m^3. Likewise, the GHG emissions produced by the Alcoutin WWTP were estimated at about 1.19 kg CO_2 e/m^3, while those generated by the Martinlongo WWTP were estimated at about 0.25 kg CO_2 e/ m^3.

Life Cycle Assessment (LCA) studies assessing and comparing the environmental impacts from the operation of CWs and CAS systems also show similar results with the present analysis [e.g. 30–34]. Garfí et al. [30] performed LCA to assess the environmental impacts of a CAS based WWTP of 1,500 p.e. in Catalonia, Spain (baseline scenario). The results of the baseline scenario were compared with two alterative scenarios of WWTPs involving (a) CWs and (b) high rate algal pond systems, instead of CAS (the alternative scenarios were designed to achieve the same effluent quality as the baseline scenario). They demonstrated that the WWTPs involving nature-based systems were more environmentally friendly wastewater treatment options compared with the CAS based WWTP, with regard to energy and chemicals consumption. The energy consumption of the CAS based system was estimated at about 12.26 kW/m^3, while the energy consumption of the CWs based system was estimated at about 0.22 kW/m^3. The potential environmental impacts of the CAS based WWTP was about 2–5 times higher compared with the CW based WWTP depending on the impact category, while the operation of the CAS based system generated about 10 kg CO_2 e/m^3 and the operation of CWs based system generated about 1.3 kg CO_2 e/m^3.

In addition, WWTPs involving CWs are expected to have similarly lower operating and maintenance costs compared with CAS based WWTPs, as can be concluded from results of previous studies. According to de Fingueiredo Simeão [29], CAS based WWTPs have significantly higher operating costs when compared with CW systems. For example, the operating costs of the Alcoutin WWTP, using CAS to serve 340 inhabitants, were 0.40 €/m^3 in 2011, while the operating costs of the Martinlongo WWTP, using CWs to serve 257 inhabitants, were 0.025 €/m^3. Gafri et al., [30] made an economic assessment of both the capital and the operating costs of CAS and CW based WWTPs showing that for both categories the costs associated with CAS were between two to three times higher than the costs associated with CWs (CAS capital cost: 540.93 €/p.e.; CWs capital cost: 210.36 €/p.e.; CAS operation and maintenance cost: 0.79 €/m^3; CWs operational and maintenance cost: 0.40 €/m^3).

Moreover, available literature indicates that the smaller the size of the community, the more appropriate the nature-based solutions are, if compared with conventional wastewater treatment systems [30,34]. However, the cost and the environmental impacts associated with the construction of CWs may be significant under specific conditions, such as limited land availability, high cost of land or use of advanced filter materials for CW design (instead of sand and gravel), as showed in Lopsik [31].

5. Conclusions

As demonstrated in this study, cNES can provide a competitive alternative to purely engineered systems for wastewater treatment and reuse. The results of the current analysis show that cNES involving CWs can be an environmental friendly solution for wastewater treatment and reuse in small or isolated communities and can contribute to addressing local water scarcity issues, as they can achieve adequate removal of pollutants and provide effluent of suitable quality for several uses, including agricultural irrigation or irrigation of public spaces. At the same time, cNES can result in significant energy savings and reduced GHG emissions compared with CAS based WWTPs (CAS systems consume about 3,000 times more energy, producing about 50 times more total GHG emissions compared with CWs).

In the present study, only the energy consumption of the aeration tank of the CAS system was considered. In order to fully analyse the energy requirements and the relevant GHG emissions of a CAS system, the sludge treatment unit should also be considered, as its energy consumption is significant [21]. In any case, the conclusions of an analysis including the sludge treatment unit would be similar to the present study, showing an even greater difference concerning the energy consumption and the relevant GHG emissions between the two systems.

In addition, cNES involving CWs are expected to have similarly lower operating and maintenance costs compared with CAS based WWTPs. The CAS process is highly mechanised and requires skilled labour and frequent maintenance. On the contrary, CWs offer construction simplicity, and have low operating and maintenance costs, especially in the context of small populations [27,29,30]. However, the investment cost of CWs may be significantly greater compared with CAS systems, as CWs need significantly larger available land [17,28]. Moreover, CWs usually require long start-up times to reach full capacity, and can generate odours or be associated with mosquito problems (mostly applies to free-water surface or horizontal wetlands), hence, they cannot be situated close to settlements [6,17,27]. In addition, the use of advance filter materials for CW design, such as lightweight expanded clay aggregate, instead of sand and gravel, may significantly raise the capital cost of CWs [31]. For these reasons, further research on the economic and social aspects that may influence the implementation of cNES (other than the energy consumption and the related emissions), including capital costs and social acceptance, as well as of the relevant market dynamics is needed to boost the market penetration and the widespread adoption of these systems.

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