Energy Savings & Reduced Emissions in Combined Natural & Engineered Systems for Wastewater Treatment & Reuse: The WWTP of Antiparos Island, Greece

P.-M. Stathatou[1*], P. Dedousis[1], G. Arampatzis[2], H. Grigoropoulou[1], D. Assimacopoulos[1]

[1]School of Chemical Engineering, National Technical University of Athens, Zografou, Athens, 15780, Greece
[2]School of Production Engineering and Management, Technical University of Crete, 73100 Chania, Greece
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Corresponding author details: pstathatou@chemeng.ntua.gr, +30 2107721024, +30 2107723155

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), in 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 in delivering safe, reliable and efficient water services. 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 an activated sludge process for the secondary treatment of effluents to achieve the same effluent quality with 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. Through this analysis the feasibility of including CWs in the treatment train to obtain water for irrigation of public spaces in isolated insular communities and small municipalities is also demonstrated.

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. Microbiological degradation processes are reduced at low temperatures; treatment performance for biodegradable compounds depends on the local climate and is affected by seasonal variations in temperature, especially by 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 cNES advantages for wastewater treatment and reuse, focusing on the energy savings and the reduction of greenhouse gas (GHG) emissions from the involved natural treatment processes. 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 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 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 with 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 & Methods

2.1 The 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). It 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.

Fig. 1 *Location of Antiparos Island, Greece*

The island faces serious development issues, due to lack of infrastructure and its isolated location. Domestic wastewater in Antiparos was until recently disposed of through septic tanks, as there was no sewage network and 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/day during winter (1,500 p.e.) and 480 m^3/day during summer (3,000 p.e.). [15]

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

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 planted with *Phragmites Australis* plants: the first stage comprises 4 sealed beds with an area of 460 m^2 each, and the second stage comprises 2 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 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) from where it is used for irrigation of public spaces located near the WWTP (restricted irrigation) (Fig. 3).

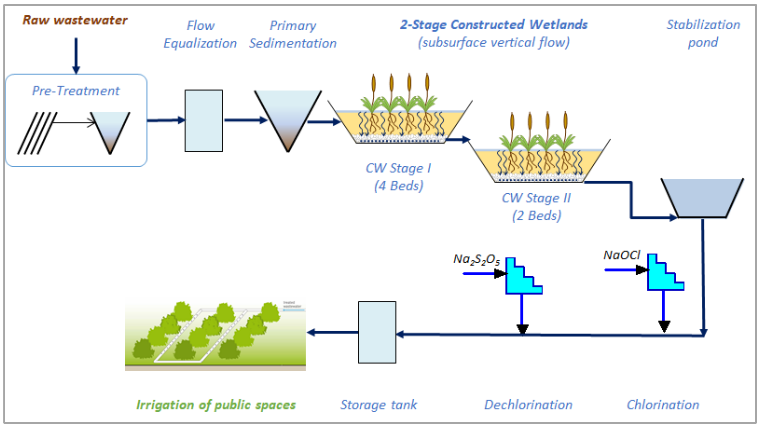


Fig. 3 *The Flow Scheme of the Antiparos cNES*

2.2 The 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 8 months (245 days) and that of the summer period 4 months (120 days).

Table 1 *Hydraulic and Pollution Loads Entering the Antiparos cNES [15]*

Parameter	Unit	Winter	Summer
Population equivalent (p.e.)	#	1,500	3,000
Mean daily flow	m^3/d	240	480
Max hourly flow	m^3/h	41	71
BOD_5	kg/d	90	180
	mg/L	375	375
Total Suspended Solids (TSS)	kg/d	105	210
	mg/L	438	438
Total Nitrogen (TN)	kg/d	18	36
	mg/L	75	75
Total Phosphorus (TP)	kg/d	3	6
	mg/L	13	13
Escherichia Coli (E. Coli)	#/100 mL	10,000,000	10,000,000
Wastewater Temperature (T)	ºC	14	22

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 is being 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 integrating modeling environment is presented in Fig. 4.

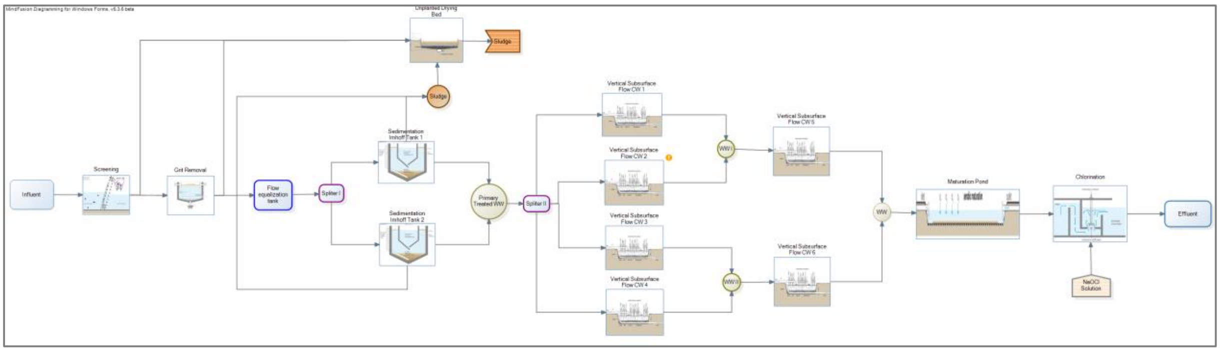


Fig. 4 *The Model of the Antiparos cNES (Baseline Scenario)*

The treatment performance of the cNES was assessed in both winter and summer conditions, through the estimation of the pollutant removal of each treatment process and the ability of the system to achieve the required quality limits for the reuse of treated effluents for unrestricted irrigation, as specified by the Greek Water Reuse Legislation (CMD 145116/2011) (Table 2) [20].

Table 2 *Provisions of the Greek Water Reuse Legislation for the reuse of treated effluents for unrestricted irrigation [20]*

Potential Use	**Minimum Required Treatment Level**	**Required Quality Limits**
Agricultural use (restricted irrigation)	Secondary biological treatment & disinfection	• E. Coli ≤200 EC/100mL (median) • BOD_5 ≤25 mg/L • TSS ≤35 mg/L • TN ≤45 mg/L

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 with 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 with 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; part of them is 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 integrating modeling environment is presented in Fig. 5.

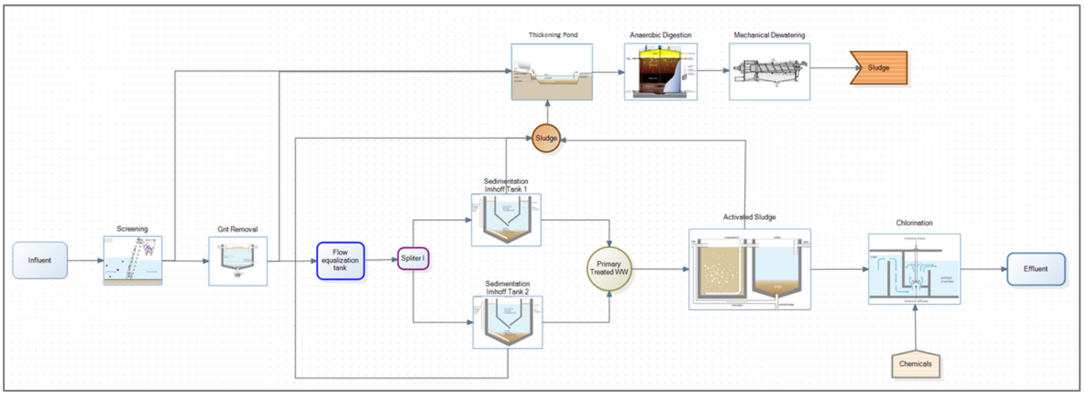


Fig. 5 *The Model of the Antiparos WWTP Involving a CAS System (Alternative Scenario)*

Table 3 *Biological Kinetic Parameters Set for the Design of the CAS System [21]*

Parameter	Unit	Winter	Summer
Cell residence time in the aeration tank, $\theta_{C,A}$	days	10.00	5.00
Mixed liquor suspended solids, MLSS	mg/L	3,500.00	3,500.00
Dissolved oxygen, DO	mg/L	2.50	2.50
Maximum heterotrophic growth rate for T = 20 ºC, $\mu_{H,max,20}$	days^{-1}	7.00	7.00
Constant, k_H	-	0.07	0.07
Monod saturation constant, K_{SH}	mg/l	120.00	120.00
Heterotrophic decay rate coefficient in endogenous respiration, b_H	days^{-1}	0.06	0.06
Heterotrophic yield coefficient, Y_H	kgVSS/kgBOD$_5$	0.65	0.65
Maximum autotrophic growth rate for T = 20 ºC, $\mu_{N,max,20}$	days^{-1}	0.60	0.60
Constant, k_N	-	0.12	0.12
Monod saturation constant, K_{SN}	mg/l	0.5	0.5
Monod half-saturation constant of DO, K_{DO}	mg/l	0.5	0.5
Autotrophic decay rate coefficient, b_N	days^{-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

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 by Dimopoulou [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 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. The aeration blower power requirements were estimated for the selected submerged aeration diffusers, and on this basis the daily and annual energy consumption for wastewater aeration was calculated (kWh/day and kWh/year respectively).

2.2.4 Calculation of GHG Emissions

Both direct / on-site GHG emissions (generated by the biological processes of the wastewater treatment facility) and indirect / off-site GHG emissions (generated by the production of the electricity consumed by the plant) were analysed.

For the baseline scenario, the on-site GHG emissions generated by the CWs were calculated following the methodology proposed by IPCC for CWs of vertical subsurface flow [23]. Methane (CH_4) emissions and nitrous oxide (N_2O) were took into account, produced in methanogenesis and nitrification / denitrification of N compounds by microorganisms respectively. 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 not considered to impact GHG emissions, as harvesting is performed rarely and the amount of harvested vegetation (quantity of harvested biomass) is generally very small.

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.

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) [24]. 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 4. The corresponding GHG emission factors for each fuel source, as proposed by Shahabadi et al., [25] are also given in Table 4. 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).

Table 4 *Fuel Mixture for Greece & GHG Emission Factors [24 & 25]*

Production Units & Interconnections	**Interconnected System (%)**	**Non-interconnected System (%)**	**GHG Emission Factor (gr CO_2 e/kWh)**
Lignite	30.85	0.00	877.00
Oil	0.00	82.39	604.00
Natural Gas	31.01	0.00	353.00
Hydroelectric	6.51	0.00	0.00
Renewable	19.89	17.61	0.00
Interconnections	11.74	0.00	0.00
Total	**100.00**	**100.00**	-

In this analysis the global warming potential (GWP) values relevant to CO_2 suggested by the latest report of the IPCC for the 100-year time horizon [26] were considered. These values, which were used for the calculation of GHG emissions in kg CO_2 equivalents, are presented in Table 5.

Table 5 *GWP Values for Selected GHG [26]*

GHG	**Chemical Formula**	**GWP values for 100-year time horizon**
Carbon Dioxide	CO_2	1
Methane	CH_4	28
Nitrous Oxide	N_2O	265

3 Results & Discussion

3.1.1 The 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 (Fig. 6, Fig. 7).

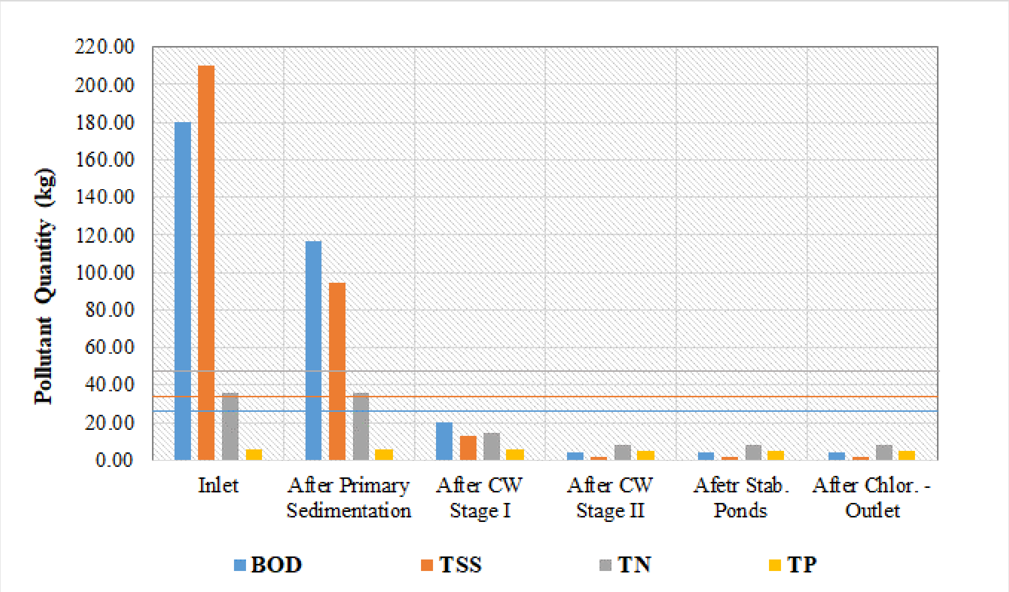


Fig. 6 *Assessment Results of Pollutant Removal in the Antiparos cNES for the Summer Period (the horizontal blue, orange and grey lines represent limits set by the Greek Reuse Legislation for restricted irrigation for BOD, TSS and TN respectively)*

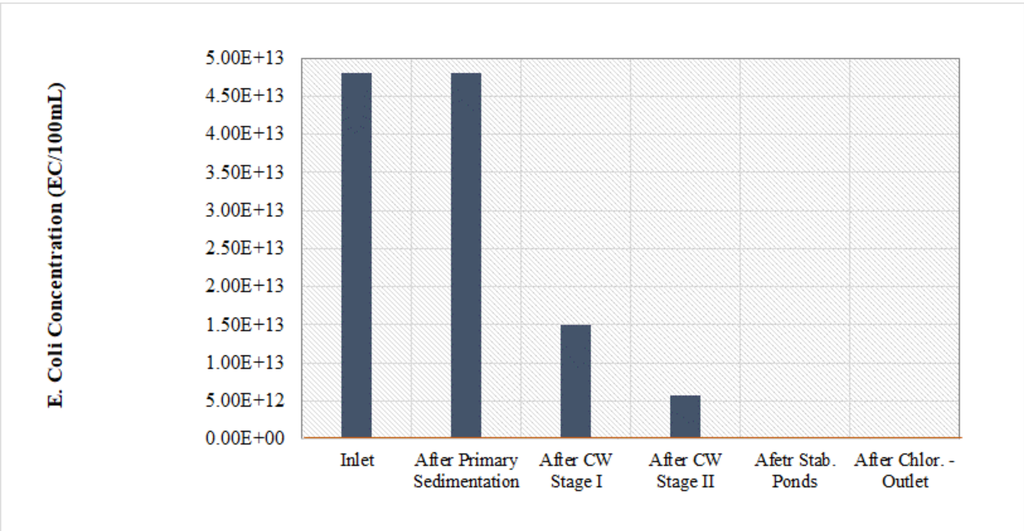


Fig. 7 *Assessment Results of E. Coli Removal in the Antiparos cNES for the Summer Period (the horizontal orange line represent limits set by the Greek Reuse Legislation for restricted irrigation)*

3.1.2 The 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 BOD5, 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.

Table 6 *Design Parameters of the Anoxic and Aeration Tanks of the CAS System*

Design Parameter	**Value**	**Units**
Anoxic Tank Volume, V_{ANOX}	100	m^3
Aeration Tank Volume, V_{AIR}	140	m^3
Total Volume of Biological Processes, V_{TOTAL}	240	m^3
Aeration Tank Depth, H_u	3	m
Required Air Flow Rate, Q_{AIR}	255 (winter) 464 (summer)	Nm^3/h
No. of Air Blowers in Operation	1 (winter) 2 (summer)	-
Air Blower Capacity	260	Nm^3/h
Blower Power Absorbed, P_w	66 (winter) 70 (summer)	kW

3.1.3 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 kW. 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 about 0.40 kW/d and 0.80 kW/d respectively, while the annual energy consumption for the operation of CWs was estimated at about 194 kW/yr.

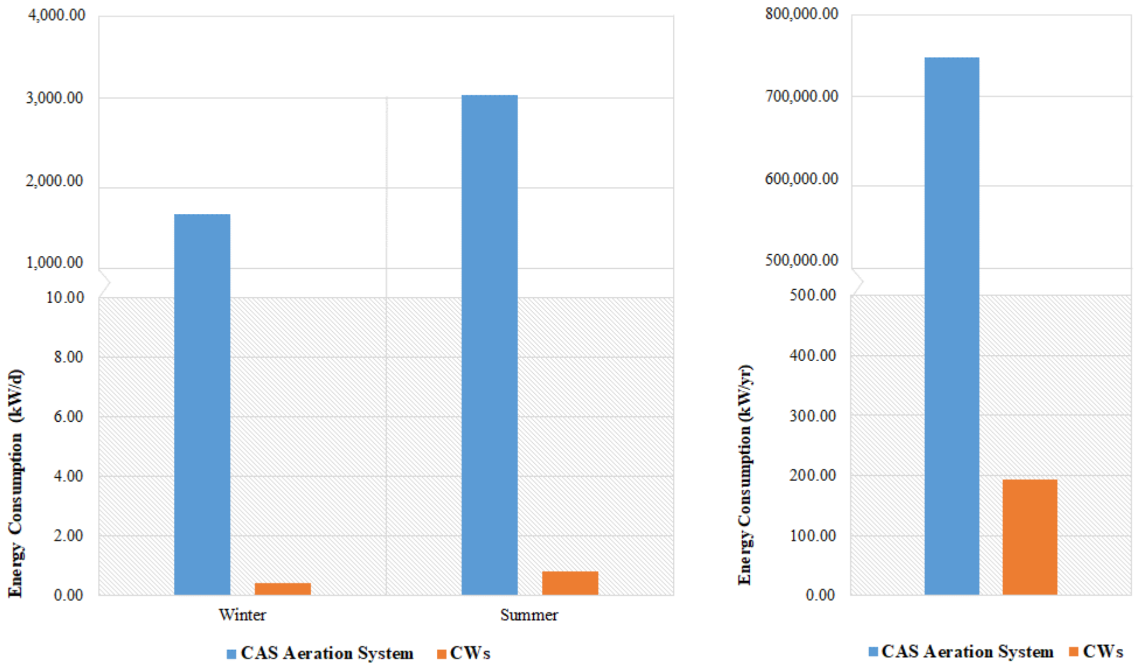
The energy consumption of the CAS aeration unit was calculated taking into consideration the operation characteristics of Table 6. The daily energy consumption for wastewater aeration was estimated at about 1,560 kW/d during winter and 3,045 kW/d during summer, while the annual energy consumption of aeration was estimated at about 747,255 kW/yr. The CAS aeration requires constant electricity supply, and its energy consumption is significantly higher (about 4,000 times greater) compared to the consumption of CWs, as presented in Fig. 8.

3.1.4 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 and 31 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; 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 for winter days and 0.40 kg CO_2 e/d for summer days. Hence, the total GHG emissions produced by CWs in the winter and summer periods were estimated at about 15.60 kg CO_2 e/d and 31.00 kg CO_2 e/d respectively.

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 on winter days and 120.00 kg CO_2 e/d 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 for a typical winter day and 1,515.00 kg CO_2 e/d for a typical summer day. Therefore, the total GHG emissions produced by the CAS in the winter and summer periods were estimated at about 884.00 kg CO_2 e/d and 1635.00 kg CO2 e/d respectively.

The total GHG emissions generated by the CAS system are about 55 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, Fig. 10 (a) and Fig. 10 (b) respectively.



(a) (b)

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*

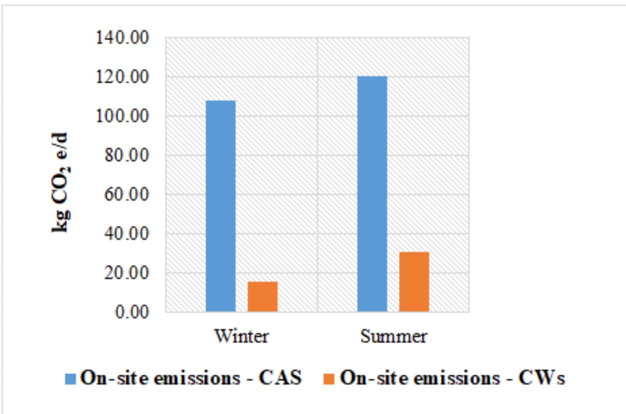


Fig. 9 *On-site GHG Emissions Generated by the CAS and the CWs in the Winter and the Summer Periods*

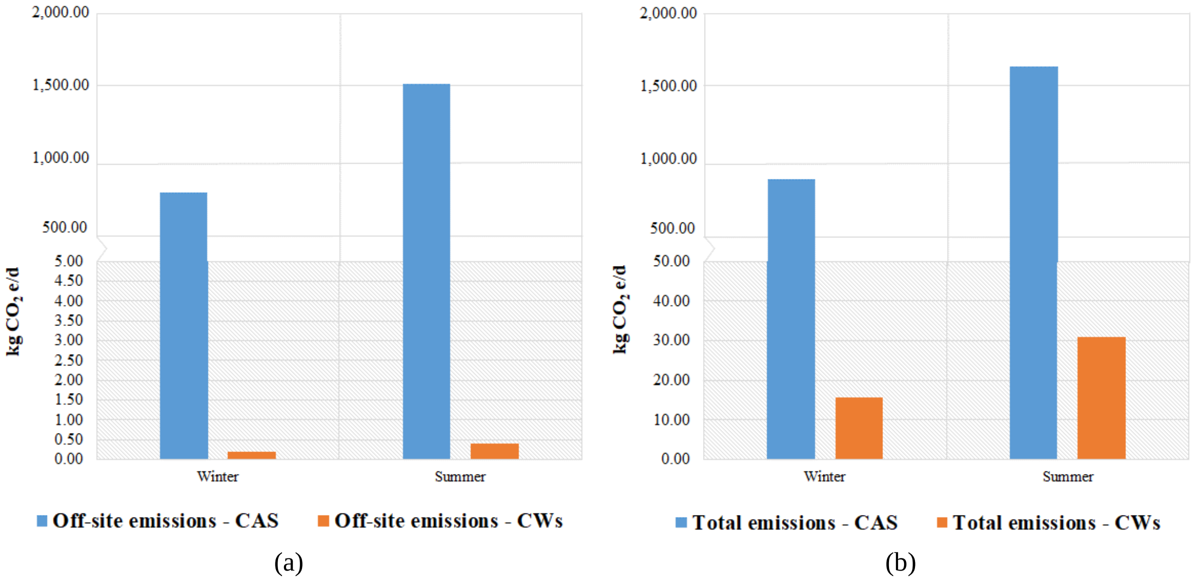


***Fig. 10** (a) Off-site GHG Emissions Generated by the CAS and the CWs in the Winter and the Summer periods; (b) Total GHG Emissions Generated by the CAS and the CWs in the Winter and the Summer Periods*

4 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 pose an environmentally friendly solution for wastewater treatment and reuse in small or isolated communities and 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 to CAS based WWTPs (CAS systems consume about 4,000 times more energy, producing about 55 times more total GHG emissions compared to 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 to 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]. However, the implementation of CWs can be limited by other economic factors, as they need significant amount of available land, 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]. Further research on the socio-economic and the policy/regulatory factors that may influence the implementation of cNES, 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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