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

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Why Combining Natural & Engineered Treatment Systems?

Europe’s water service providers struggling to deliver improved & affordable water services

- Continuous population growth
- Climate change

Natural water treatment processes

- Ecological & socio-economic advantages over purely engineered systems
  - Lower operational costs & energy requirements
  - Conservation of natural environment
  - Zero visual obstruction
- Performance limitations
  - Low temperatures
  - Space restrictions
  - Long residence times
  - Flow variations during floods and droughts

Combination of natural with engineered treatment processes to overcome limitations, improve performance & increase treatment resilience of natural processes

Research on Combined Natural & Engineered Treatment Systems (cNES)

Investigating & assessing the potential advantages of cNES over purely engineered treatment systems in delivering safe, reliable and efficient water services

Aim of the study

- Assess cNES advantages for wastewater treatment and reuse, focusing on the energy savings and the reduction of GHG emissions
- Demonstrate the feasibility of cNES to obtain water for irrigation of public spaces in isolated insular communities and small municipalities

The Study Site Area

Antiparos Island, Greece

Location of Antiparos Island, Greece

Location & Administration

- Located in the Cyclades complex of the Aegean sea
  - Area: 35.10 km^2
  - Permanent population: 1,211 inh. (cencus 2011)
  - Seasonal residents & tourists: 1,000 (2012)
- Administration: Municipality of Antiparos
  - Public entity
  - Part of the Regional Unit of Paros

The Problem of Untreated WW

- Drivers
  - Lack of infrastructure
  - Isolated location
  - Rapid tourism development
- Impacts on natural & socio-economic environment
  - Groundwater & marine contamination
  - Development issues & impacts on tourism

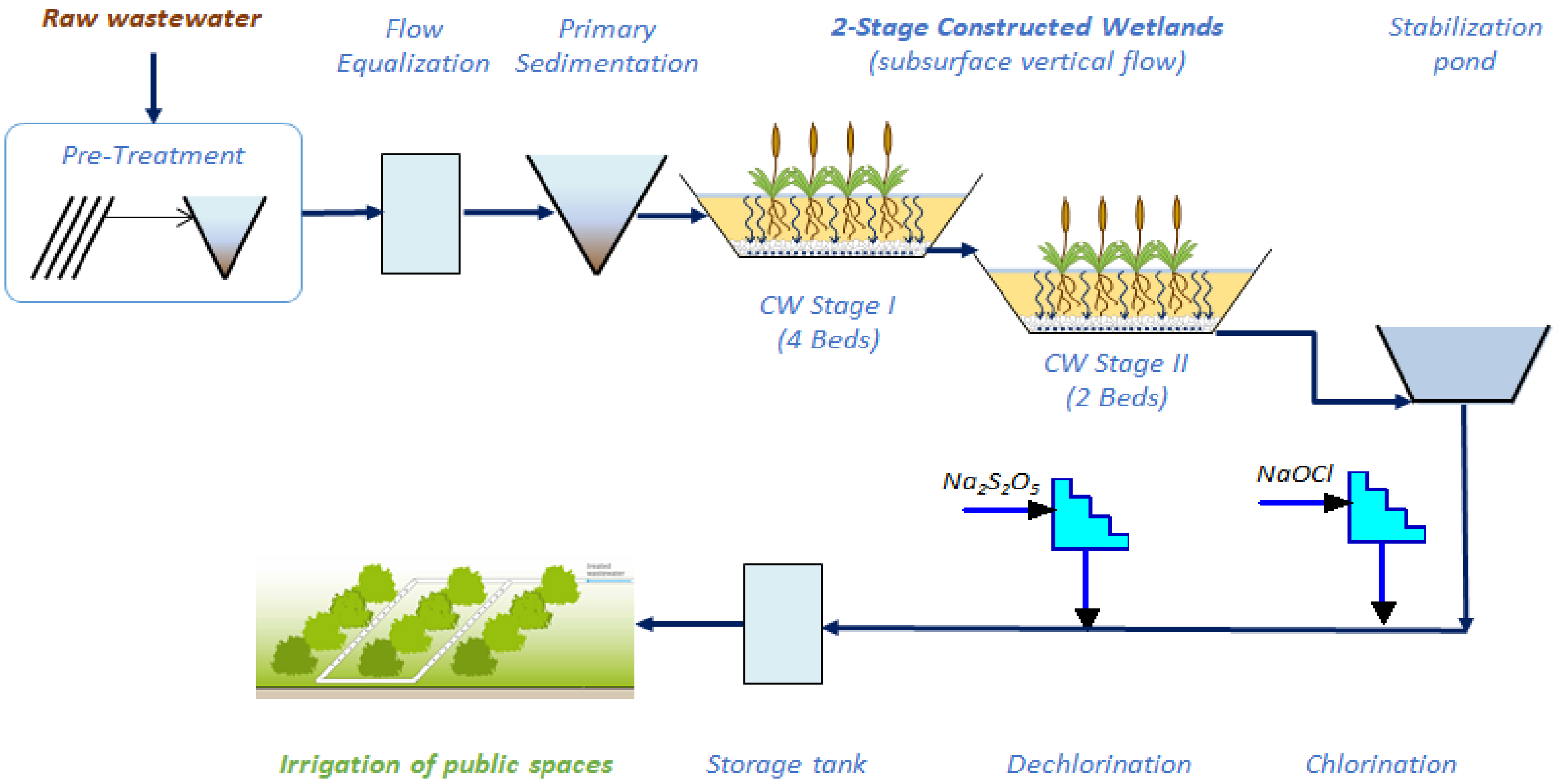
- **Suggested Solution**
  - ***The WWTP of Antiparos***

The WWTP of Antiparos Island

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

- Constructed in **May 2015** for the **treatment & reuse of municipal wastewater**
- Located at **Sifneikos Gyalos**
  - Area: 28,400 m^2
- Mean daily design capacity (year 2035)
  - **240 m^3/d** during winter (1,500 p.e.)
  - **480 m^3/d** during summer (3,000 p.e.)

Flow Scheme of the Antiparos cNES



Raw wastewater

Flow Equalization

Primary Sedimentation

2-Stage Constructed Wetlands
(subsurface vertical flow)

Stabilization pond

Pre-Treatment

CW Stage I (4 Beds)

CW Stage II (2 Beds)

$Na_2S_2O_5$

NaOCl

Irrigation of public spaces

Storage tank

Dechlorination

Chlorination

The Adopted Methodology

1. Modeling of the Antiparos cNES (Baseline Scenario)

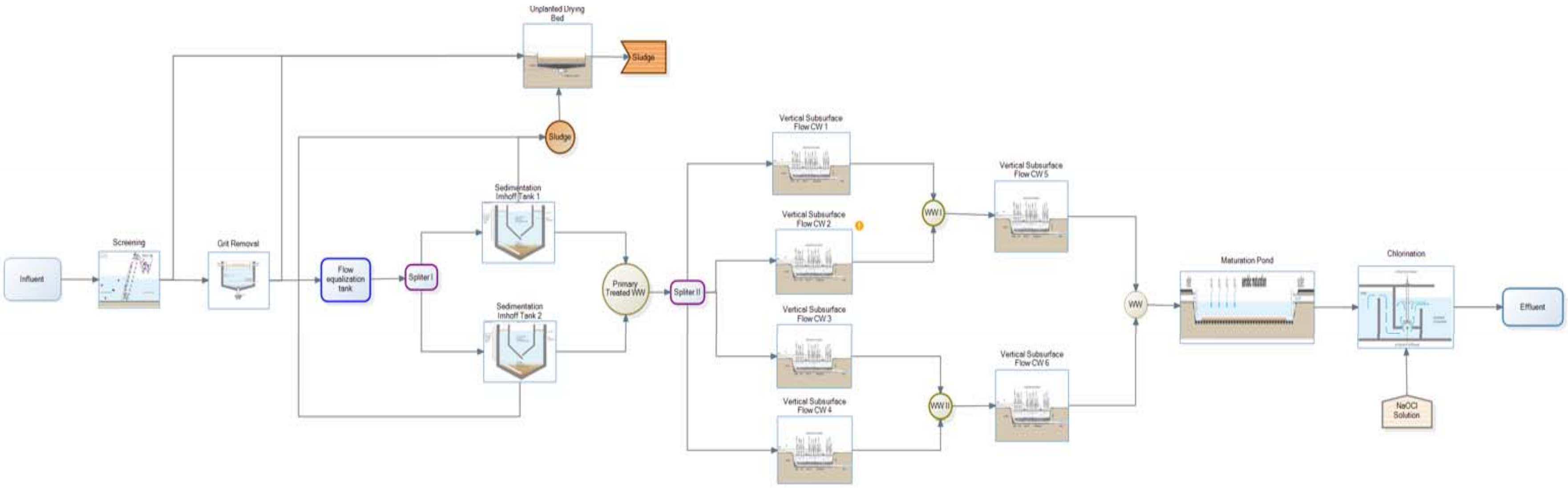
- Integrating software modelling & simulation environment
  - Building a cNES by integrating libraries for the modeling of engineered & natural treatment processes & their interactions
  - Evaluating the quantity & quality of wastewater, the generated sludge & emissions, the energy consumed & the chemicals used

- Model assumptions
  - Winter duration: 8 months (245 days)
  - Summer duration: 4 months (120 days)
  - Generated sludge at pre-treatment stage: 0.03 L/m^3
  - Primary sedimentation: 55% reduction of TSS and 35% reduction of BOD_5

Hydraulic and Pollution Loads Entering the Antiparos cNES (Source: Egnatia S.A, 2012)

Parameter	Unit	Winter	Summer
P.E.	#	1,500	3,000
Mean daily flow	m^3/d	240	480
BOD_5	kg/d	90	180
	mg/L	375	375
TSS	kg/d	105	210
	mg/L	438	438
TN	kg/d	18	36
	mg/L	75	75
TP	kg/d	3	6
	mg/L	13	13
E. Coli	#/100 mL	10,000,000	10,000,000
T	°C	14	22

The Model of the Antiparos cNES (Baseline Scenario)



Assessment of the Antiparos cNES (Baseline Scenario)

- Treatment performance was assessed in both winter & summer conditions
- Estimation of pollutant removal of each treatment process
- Assessment of the ability of the system to achieve the required quality limits
  - **Greek Water Reuse Legislation (CMD 145116/2011)** for the reuse of treated effluents for unrestricted irrigation

Provisions of the Greek Water Reuse Legislation for the reuse of treated effluents for unrestricted irrigation (Source: CMD 145116/2011)

Reuse of treated effluents for restricted irrigation	
Minimum Required Treatment Level	Secondary biological treatment & disinfection
Required Quality Limits	• E. Coli ≤200 EC/100mL (median) • BOD5 ≤25 mg/L • TSS ≤35 mg/L • TN ≤45 mg/L

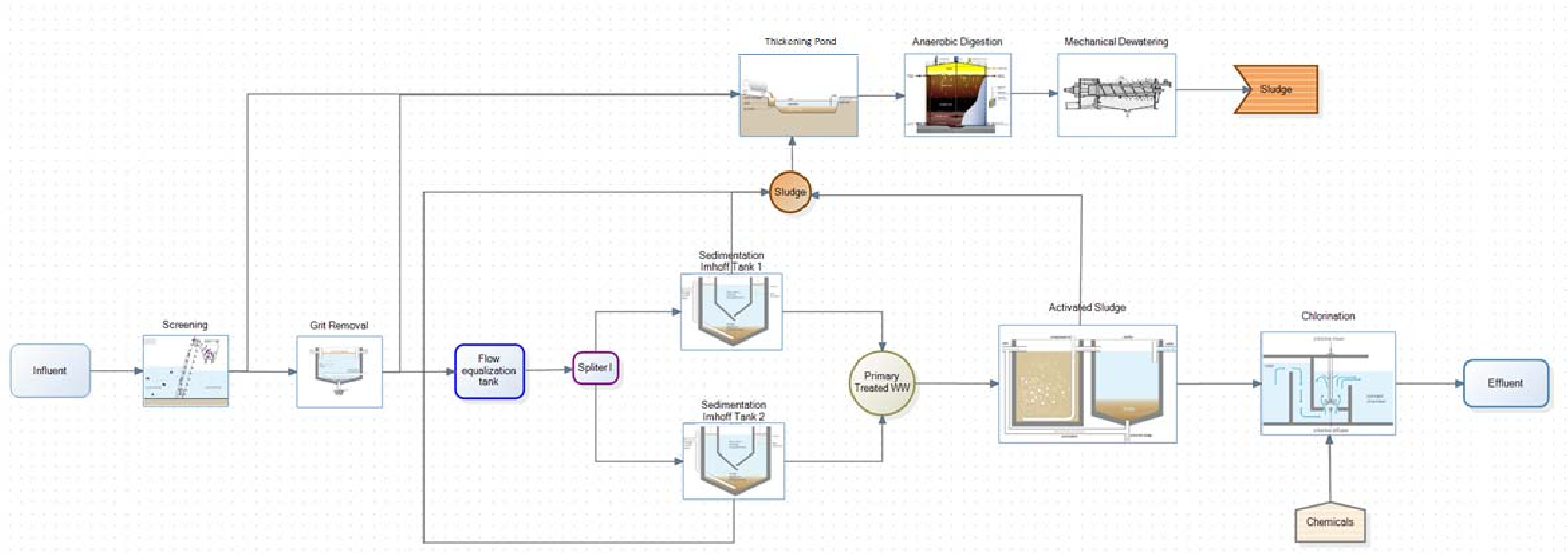
2. Design of an Activated Sludge Process for the Antiparos WWTP (Alternative Scenario)

- Substitution of CWs & stabilization pond with a conventional activated sludge process (CAS)
  - Anoxic tank for effluent nitrification / denitrification
  - Aeration tank - bioreactor
    - Submerged aeration diffusers
  - Secondary clarifier - settling tank
- The CAS was designed to achieve the same effluent quality with the CWs
  - BOD5, TSS, TN and TP
- The whole system was modelled to reach the same effluent quality at the outlet with the baseline scenario
  - BOD5, TSS, TN, TP, and E. Coli

Biological Kinetic Parameters Set for the Design of the CAS System (Adapted from Dimopoulou, 2011)

Parameter	Unit	Winter	Summer
Cell residence time in 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
Max het. 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
Het. decay rate coef. in endogenous resp., b_H	days^{-1}	0.06	0.06
Het. yield coefficient, Y_H	kgVSS/kgBOD$_5$	0.65	0.65
Max. autot. 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	0.50	0.50
Monod half-saturation constant of DO, K_{DO}	mg/L	0.50	0.50
Autotrophic decay rate coefficient, b_N	days^{-1}	0.05	0.05
Autotrophic yield coefficient, Y_N	kgVSS/kgBOD$_5$	0.15	0.15
% of inert SS entering the biological reactor, α	kgVSS/kgBOD$_5$	0.10	0.10
% of inert suspended het. bacteria, β	kgVSS/kgBOD$_5$	0.20	0.20
VSS/TSS ratio	-	0.70	0.70

The Model of the Antiparos WWTP (Alternative Scenario)



3. Calculation of Energy Consumption

Baseline Scenario

- Energy consumption recorded by the electricity meter box of the plant (kWh) for the first 30 months of operation
- Estimated that CWs contribute about 10% to the total energy consumption of the plant
  - Power needed for their feeding system

Alternative Scenario

- Only the energy consumption of the aeration tank was considered (following the approach of Dimopoulou, 2011)
- Calculation of daily & annual energy consumption for WW aeration (kWh/d & kWh/yr.)
  - Aeration flow requirement
  - Selection of submerged aeration diffusers of suitable capacity for air diffusion in the aeration tank
  - Aeration blower power requirements for the selected submerged aeration diffusers

4a. Calculation of On-Site GHG Emissions

On-site GHG emissions are generated by the biological treatment processes

Baseline Scenario - CWs

- CH_4 emissions in methanogenesis
  - Organic material load in CWs
- N_2O in nitrification / denitrification of N compounds by microorganisms
  - TN load in CWs

Alternative Scenario - CAS

- CO_2 emissions from biomass decay and oxidation
- N_2O emissions from denitrification processes

- The IPCC (2014) GWP values relevant to CO_2 for 100-year time horizon were considered
  - CH_4: 28
  - N_2O: 265

4b. Calculation of Off-Site GHG Emissions

Off-site GHG emissions are generated by the production of the electricity consumed by the plant

Fuel Mixture for Greece in 2017 & GHG Emission Factors
(Source: Public Power Corporation S.A. Hellas, 2018; Shahabadi et al., 2009)

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**	-

- Antiparos island was considered to be part of the non-interconnected system

Assessment Results

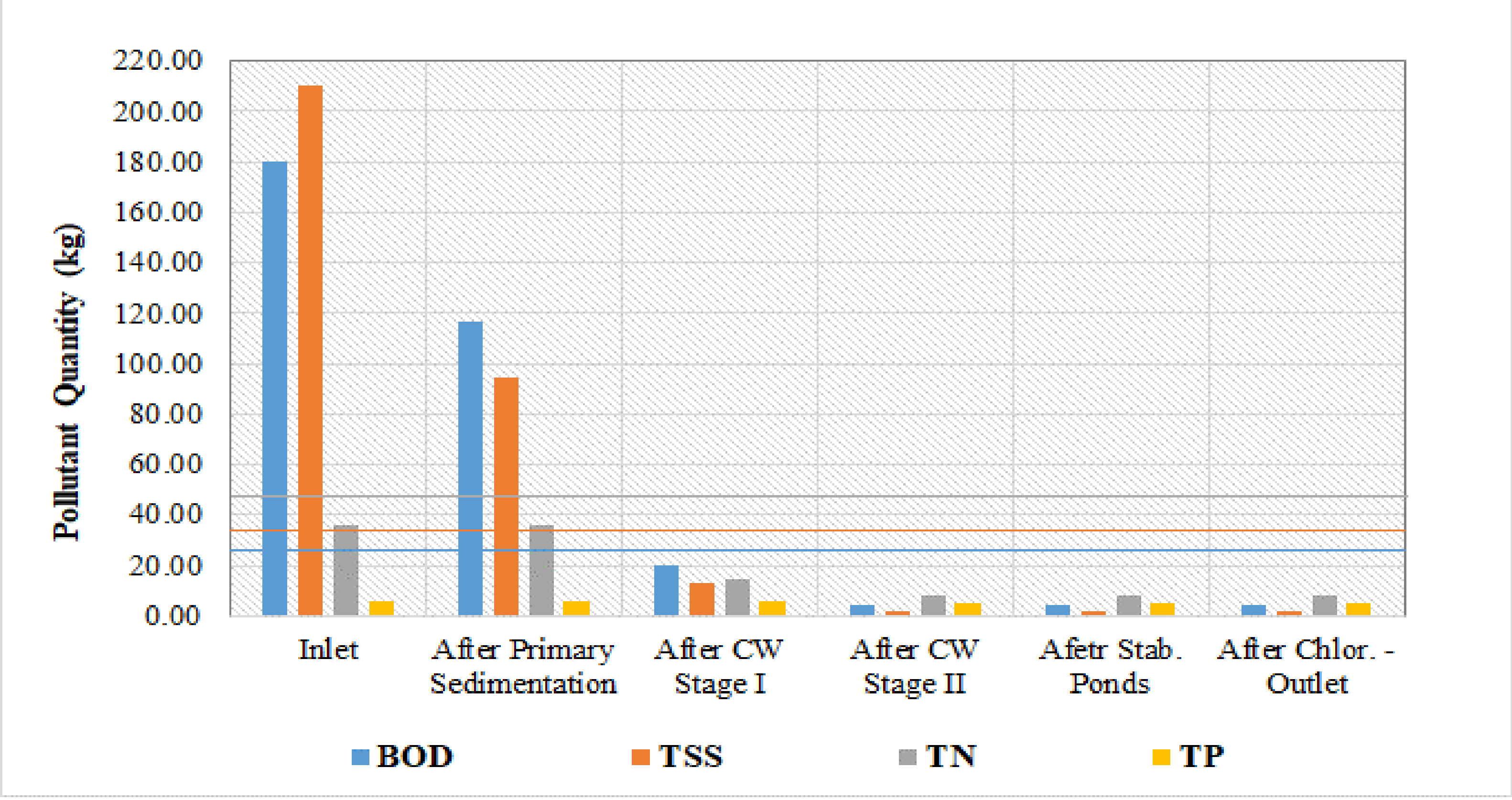
1. Treatment Performance of the Antiparos cNES (Baseline Scenario)

- Substantial contribution of CWs in the treatment - significant pollutant reduction
  - BOD5 96%
  - TSS 98%
  - TN 77%
  - TP 14%

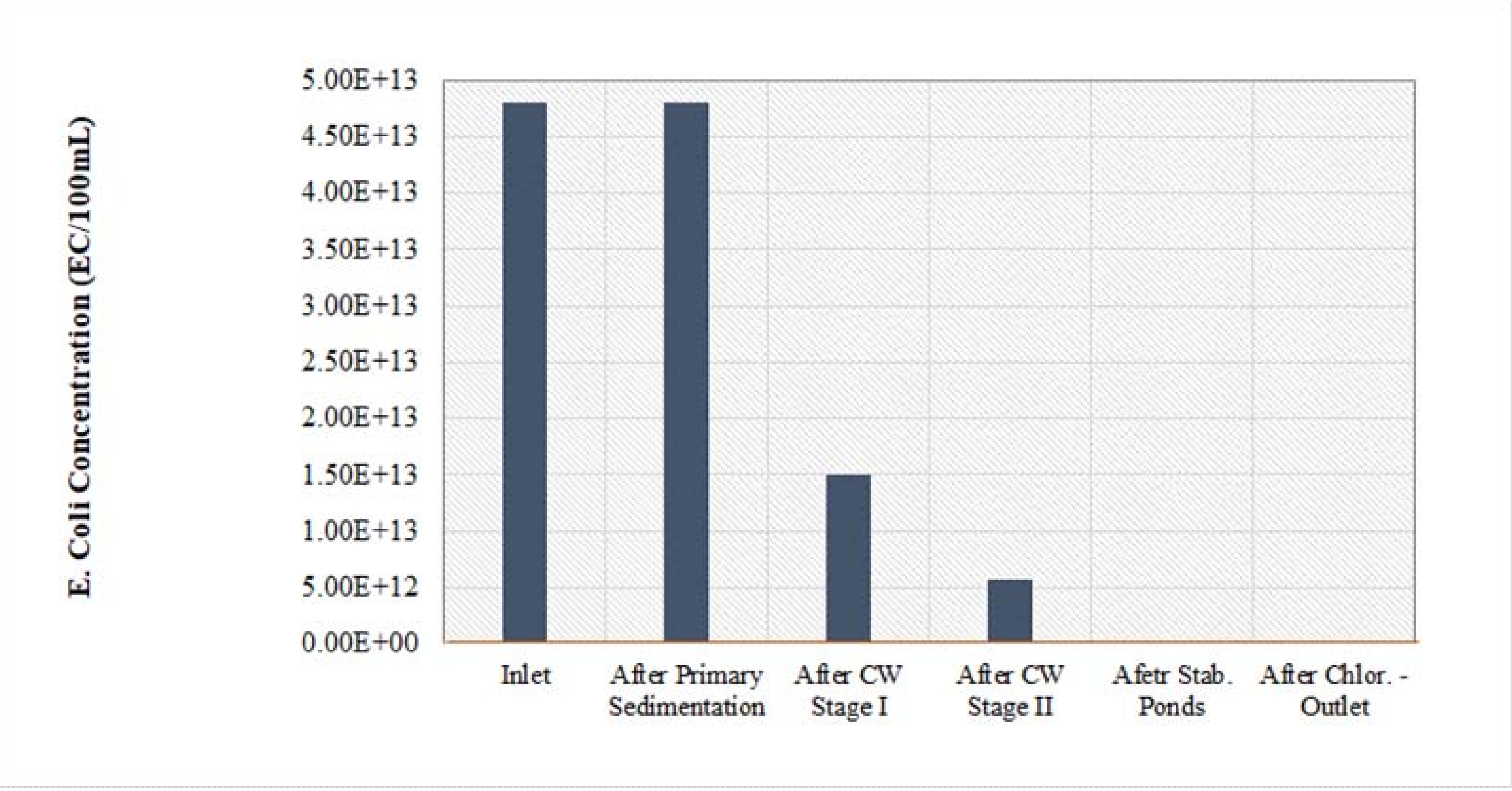
- Pathogen elimination by combining CWs, maturation pond & disinfection
  - 88% of pathogens were removed after CWs
  - 96% of pathogens entering the stabilization pond were removed

- The limits of the Greek Reuse Legislation for restricted irrigation are met - reliable performance of the system

Pollutant Removal in the Antiparos cNES



E. Coli Removal in the Antiparos cNES



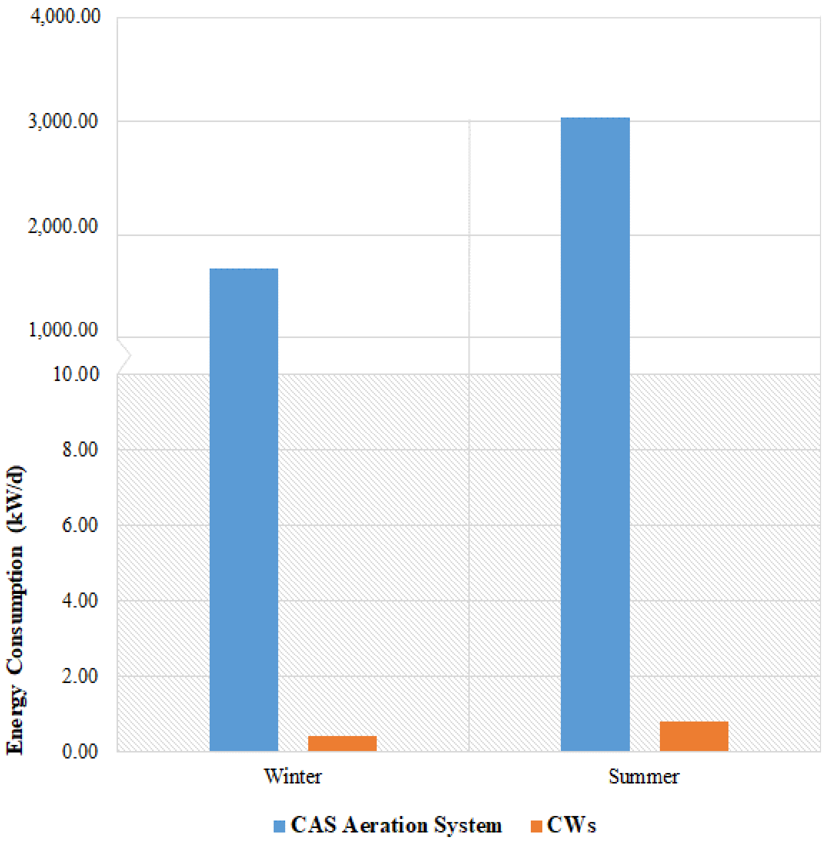
2. The CAS System for the Antiparos WWTP (Alternative Scenario)

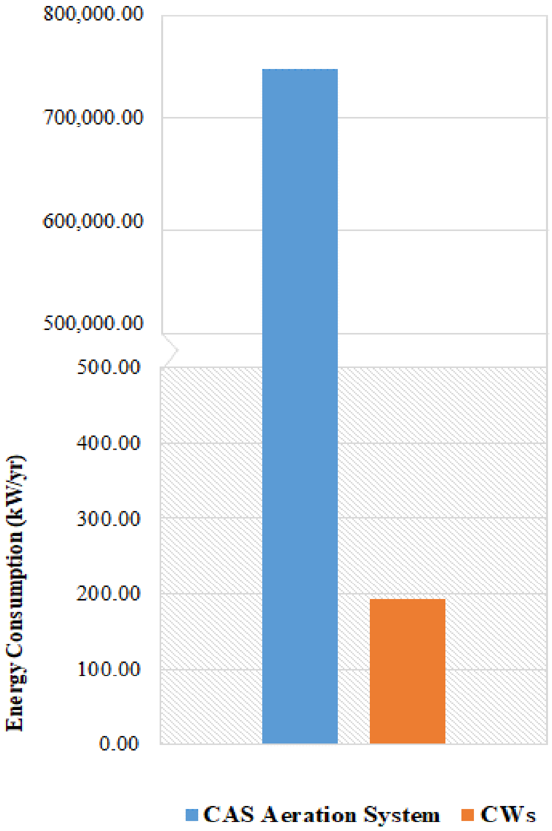
- CAS for secondary treatment instead of CWs & maturation pond to achieve the same effluent quality with the baseline scenario

Design Parameters of the Anoxic and Aeration Tanks of the CAS

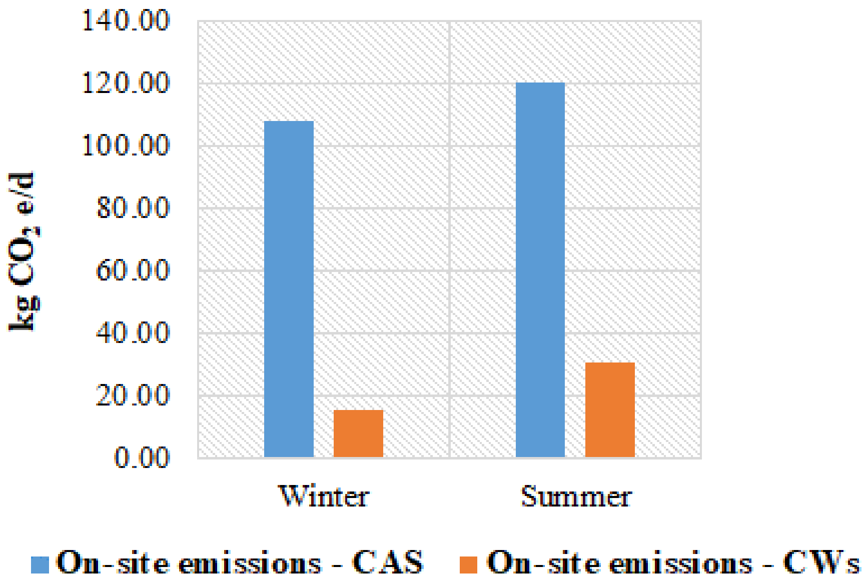
Design Parameter	Value	Units
Anoxic Tank Volume, V_{ANOX}	100	m^3
Aeration Tank Volume, V_{AIR}	140	m^3
Total Volume of Biological Processes, V_{TOTAL}	240	m^3
Aeration Tank Depth, H_u	3	m
Required Air Flow Rate, Q_{AIR}	255 (winter) 464 (summer)	Nm^3/h
No. of Air Blowers in Operation	1 (winter) 2 (summer)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

3. Comparison of Scenarios: Energy Consumption





4a. Comparison of Scenarios: On-Site GHG Emissions

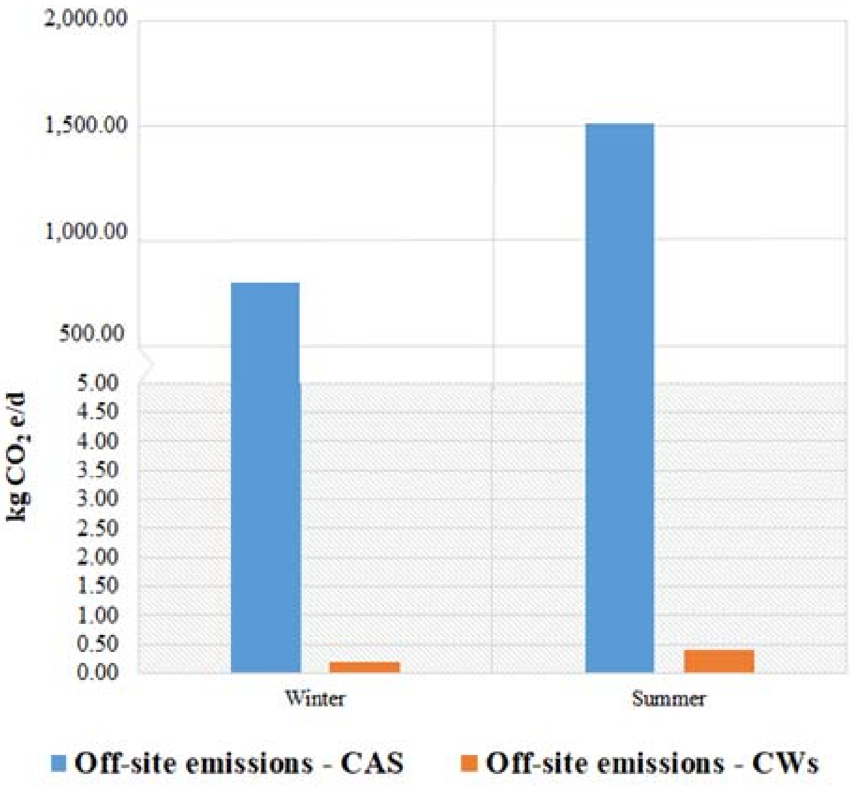


- Baseline Scenario - CWs
  - 15.50 kg CO_2 e/d on winter days
  - 31 kg CO_2 e/d on summer days

- Alternative scenario –CAS
  - 108.00 kg CO_2 e/d on winter days
  - 120.00 kg CO_2 e/d on summer days

- On-site emissions from CAS about 5 times greater than those from CWs

4b. Comparison of Scenarios: Off-Site GHG Emissions

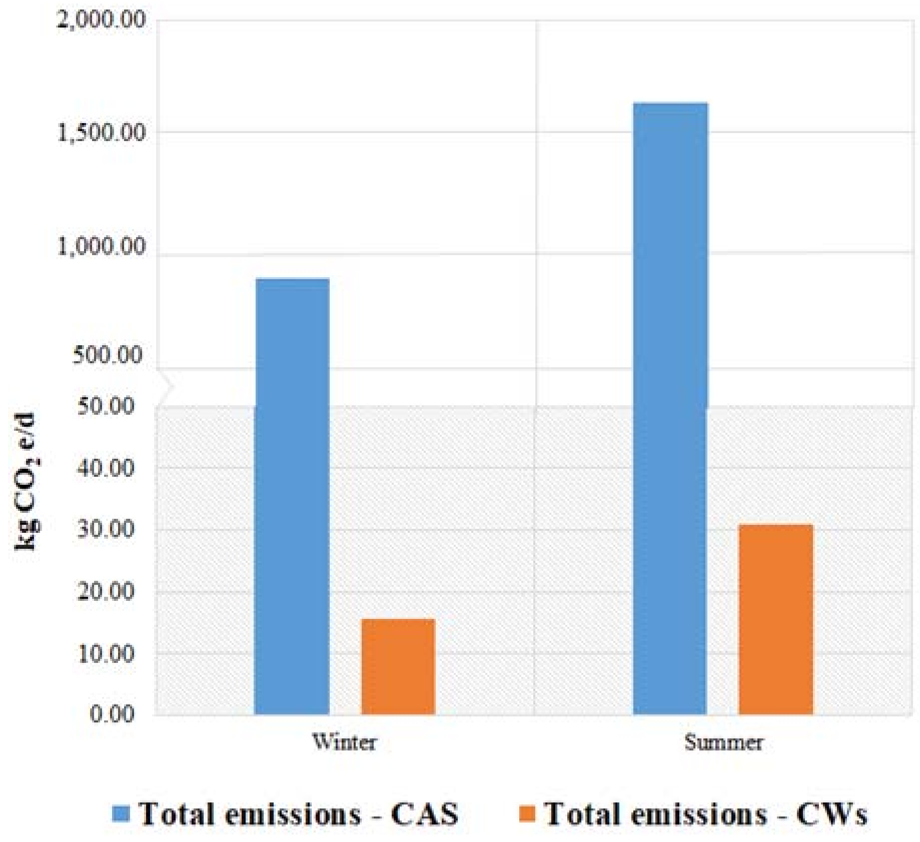


- Baseline Scenario - CWs
  - 0.20 kg CO_2 e/d on winter days
  - 0.40 kg CO_2 e/d on summer days

- Alternative scenario –CAS
  - 775.00 kg CO_2 e/d on winter days
  - 1,515.00 kg CO_2 e/d on summer days

- Off-site emissions from CAS about 4,000 times greater than those from CWs

4c. Comparison of Scenarios: Total GHG Emissions



- Baseline Scenario - CWs
  - 15.60 kg CO_2 e/d on winter days
  - 31 kg CO_2 e/d on summer days
- Alternative scenario –CAS
  - 884.00 kg CO_2 e/d on winter days
  - 1,635.00 kg CO_2 e/d on summer days
- Total emissions from CAS about 55 times greater than those from CWs

Conclusions

- cNES involving CWs can provide a competitive alternative to purely engineered systems for WW treatment & reuse in small or isolated communities
  - Environmentally friendly solution - significant energy savings & reduced GHG emissions compared to CAS based WWTPs
  - Adequate removal of pollutants - effluent of suitable quality for several uses

- CWs are expected to have similarly lower operating & maintenance costs compared to CAS
  - CAS process is highly mechanised and requires skilled labour & frequent maintenance
  - CWs offer construction simplicity & have low maintenance needs
    - Other limiting factors: land availability, long start-up times to reach full capacity, odour generation, mosquito problems

- Consideration of the energy consumed by the sludge treatment unit to fully analyse the energy requirements & relevant GHG emissions of a CAS system
  - Similar results to the present study are expected
  - Even greater difference between the two systems

- Further research on socio-economic, policy/regulatory factors & relevant market dynamics to boost market penetration of cNES

Acknowledgments

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Thank you for your attention!

cNES Treatment Technologies

Pre treatment: Engineered Systems

- Screening & grit removal
  - Two coarse screens
  - Aerated grit chamber
- Sedimentation
  - Two Imhoff tanks

Imhoff tanks for WW sedimentation

Secondary treatment: Natural Systems

- **Two Stages of Constructed Wetlands**
  - Six sealed beds of vertical subsurface flow, planted with common reeds
    - 4 beds for stage I (460 m^2 each)
    - 2 beds for stage II (750 m^2 each)
- **Stabilization Pond**
  - Average depth: 1.5 m
  - Minimum retention time: 7 days, during winter

The two stages of CWs & the stabilization pond

Post treatment: Engineered Systems

- Disinfection: Chlorination – Dechlorination
  - Chlorination tank: Addition of NaOCl
  - Dechlorination well: Addition of $Na_2S_2O_5$

Chlorination & dechlorination stages