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# The Role of Biomethane from Sewage Sludge in the Energy Transition: Potentials and Barriers in the Arab Gulf States Power Sector

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**Abstract:** The increasing energy and water demands by the Arab Gulf states highlight the importance of sustainable use of energy resources. Wastewater sludge management for energy recovery creates an opportunity for sector integration for both wastewater treatment plants and renewable energy production. The objective of this study was to theoretically estimate the biomethane potential of wastewater sludge, together with identification of the role of biomethane in the region. The prediction of biomethane potential was based on the theoretical stoichiometry of biomethanation reactions, using the R-based package 'Process Biogas Data and Predict Biogas Production'. The biomethane potential of sludge ranges between  $232-334 \times 10^6 \text{ m}^3$ , with a total heat-value up to 10.7 trillion BTUs annually. The produced biomethane can generate up to 1665 GWh of electric energy, an equivalent amount to the current levels of electricity generation from wind and solar power combined. The findings from the case study on Kuwait's indicate that biomethane could displace  $13 \times 10^6 \text{ m}^3$  of natural gas, or approximately 86,000 barrels of crude oil, while simultaneously reducing greenhouse gas emissions by 86% when compared to the base-scenario. Despite its potential, biomethane recovery in the region is hindered by technical-, economic-, and policy-based barriers.

**Keywords:** biomethane potential; energy transition; wastewater sludge; anaerobic digestion; biogas; waste-to-energy



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# 1. Introduction

The continuous growth in energy demand in the light of climate change and energy security concerns is driving countries to transition to alternative and renewable energy sources to reduce the reliance on traditional fossil fuels. While decarbonizing the energy sector is the key driver of the energy transformation, there are other factors for the transition. Falling renewable energy costs, jobs creation, energy access, human health and air quality, and energy security goals are additional factors driving energy transition [1]. Renewable energy accounts for approximately 10% of the global energy supply in 2018, of that share, bioenergy has the largest hold 70% of the total renewable energy supply [1,2]. While the photovoltaics and wind energies are expected to experience the largest growth rates between 2019 and 2024 [3]. Bioenergy has a significant role in the energy transition process and decarbonization of the power/heating sectors if sourced from sustainable and affordable feedstocks. In addition, the versatility and flexibility of biofuel states (solid, liquid, gaseous) render bioenergy attractive for implementation within multiple sectors, including their utility as liquid fuels for transportation, as solid biomass for heat generation

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(through incineration), and as biogas for combined heat and power (CHP) production. Biogas is produced during the anaerobic-based biological processing of biodegradable organic compounds, known as anaerobic digestion (AD). Biogas is produced from a variety of feedstocks that are typically grouped into the following categories: crop residues and other agricultural feedstock, animal manure, organic waste within municipal solid waste, together with wastewater and wastewater sludge [4–6]. Raw biogas typically contains 60% methane (CH<sub>4</sub>), 40% carbon dioxide (CO<sub>2</sub>), and other impurities (mostly H<sub>2</sub>S, H<sub>2</sub>O, and H<sub>2</sub>).

Bioenergy has the potential to play a role as a flexible resource within the renewable and variable power supply systems (wind and solar). In order to offset variability and increase the reliability of power supplies, dispatchable and flexible power plants—such as natural gas plants—are expected to play an important role in the energy transition process. Further decarbonization of the power sector is possible through expanded use of biomethane (a renewable natural gas), mainly upgraded from biogas [7–10]. The utilization of biogas and biomethane can reduce GHG emissions by substituting fossil fuels and by avoiding CO<sub>2</sub> and CH<sub>4</sub> emissions from the decomposition of organic waste during storage and disposal. However, the production of biogas through AD also constitutes a source of both such gases. Consequently, the assessment for potential reduction of GHG emissions (mainly CO<sub>2</sub>) through biogas and biomethane is complex, since it largely depends on the type of feedstock, collection and transportation, production processes, CH<sub>4</sub> leakage and end use. The CO<sub>2</sub> emissions from biogas are affected by biomass production (carbon negative), biomass-to-biogas production (nearly carbon natural), and biogas end use (carbon positive) [11].

### 1.1. Power Demands and Wastewater Generation in the Arab Gulf States

The increasing power demands and wastewater generation by the Arab Gulf, more specifically the Gulf Co-operation Council (GCC) states highlight the importance of sustainable use of energy resources. According to the International Energy Agency, power generation units and water desalination plants within the GCC region consume approximately 15–27% of all energy available for domestic use [2]. The electricity and desalination plants are powered by crude/gas oils, heavy fluid oil and natural gas.

Electricity consumption in the GCC region grew at an annual rate of 4% between 2014 to 2018, where Saudi Arabia and the UAE accounted for 52% and 19.8% of the total electricity consumption, respectively. Additionally, the volume of municipal wastewater has been steadily increasing at an annual rate of 5% (Figure 1). As of 2019, the total wastewater generation within the GCC region alone was approximately  $4763 \times 10^6 \, \mathrm{m}^3$ , where Saudi Arabia and the UAE accounted for 65% and 16% of the total wastewater volume, respectively. Wastewater sludge management for the energy recovery creates an opportunity for sector integration for both wastewater treatment plants and renewable energy production.

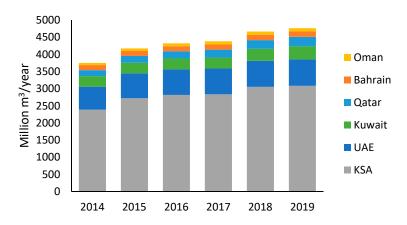


Figure 1. GCC wastewater influent. Data source [12].

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As of 2020, the renewable energy share of the total-installed power capacity was 3271 MW, or 2% of the total capacity [13]. Solar power is the dominant form of renewable energy in the GCC region, accounting for 96% of the total renewable energy sources, followed by wind and bioenergy, respectively [13]. In addition, natural gas has become a valuable oil-substitute energy source for domestic power generation (Table 1). It is worth noting that Qatar is the only member state in the GCC region where bioenergy is integrated within its energy profile. Scientific literature on bioenergy production and utilization in the GCC region is still limited. Biogas production potential and feedstock analysis were addressed by multiple investigations [4,14–18], together with similar studies on biofuels [19–22] and the potential of municipal solid waste incineration and syngas production [23,24].

**Table 1.** Electrical power generation in the GCC region by energy type (GWh). Data source (GCC-STAT, 2021).

	Crude and Oil	Natural Gas	Wind	Solar	Bioenergy	Total Renewables
2014	221,872	369,389	3	374	121	497
2015	241,053	398,121	3	379	121	503
2016	208,611	443,796	1	455	121	577
2017	189,219	486,088	24	1626	121	1078
2018	175,439	509,615	24	1610	121	1770

#### 1.2. Energy Recovery from Wastewater Sludge

Liu et al., [25] reviewed the differing technologies for energy recovery from municipal wastewater sludge. The study concluded that moisture content levels within sludge substantially affect the energy requirements for many of the energy recovery options, especially those that require dewatering and drying, such as incineration and pyrolysis [25]. Tyagi & Lo [26] presented a review of the types of resources that could be recovered from waste sludge, together with the methods employed to convert sludge into valuable resources. According to this study, AD is a well-established methodology and is widely used due to its cost-effectiveness and dual purpose (sludge stabilization and energy production) [26]. However, the main disadvantage is the slow-paced hydrolysis of sludge, which can be overcome by physical and chemical modifications to the process [26]. One major limitation of AD is its inability to decompose organic matter completely, with the by-product consisting of digestate [27]. Cao & Pawłowski [27] concluded that the efficiency of sludge-to-energy conversion can be enhanced through AD followed by a pyrolysis step (fed with digestate), which converts organic matter into bio-oil, biochar, and pyrolytic gas. Another limitation of AD is the prolonged sludge retention time within the digester, approximating a timeframe of 10–20 days. Elalami et al., [28] addressed the limitation of municipal wastewater sludge as a feedstock to produce CH<sub>4</sub>, since AD sludge typically contributes low CH<sub>4</sub> yields in comparison to other types of organic waste.

#### 2. Objectives

The objective of this study is to investigate the regional scale biomethane potential for the GCC member states using publicly available data on wastewater and sludge. The study aims to assess the role of biogas and biomethane from sludge in the energy transition in the region and quantify the potential fossil fuels savings and emissions reduction. Additionally, this study serves to highlight the barriers and drivers for the deployment of biogas and biomethane in the GCC region.

#### 3. Prediction of Biochemical Methane Potential

The theoretical amount of biogas and biomethane production is referred to as biochemical methane potential (BMP). It is an important parameter used in evaluating the productivity of organic materials (feedstock) in producing biogas and CH<sub>4</sub>. There are

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numerous methods to estimate the BMP of feedstocks. Jingura and Kamusoko [29] classified all current BMP estimation methods into experimental and theoretical methods, and reviewed the advantages and disadvantages of both groups. Most experimental techniques consist of laboratory-scale batch assays that utilize manometric, volumetric, and gas chromatography methods to measure CH<sub>4</sub> production.

Experimental BMP methodologies mimic AD conditions on a practical level and such estimates are valid and reliable. However, the main drawbacks of such methodologies include relatively high costs and the length of time required for obtaining results [29]. Conversely, theoretical methodologies are employed for predicting BMP from readily available feedstock parameters, such as elemental/chemical compositions and chemical oxygen demand (COD). The utility elemental composition (C, H, O, S, N) of a substrate as a predictor of BMP is based upon Buswell's stoichiometric formula [30], which assumes that organic matter is completely biodegraded to CH<sub>4</sub> and CO<sub>2</sub>. In contrast, McCarty [31] proposed a modified bioenergetics and stoichiometry approach which takes into account the fraction of substrate used for cellular synthesis and energy production (CH<sub>4</sub>). Furthermore, in cases where elemental composition of the substrate is unknown, the chemical composition (mainly carbohydrates, proteins and lipids) can alternatively be used to determine BMP. Godin et al. [32] demonstrated the reliability of chemical composition as a predictor of BMP using statistical models, though the accuracy of such a prediction is sensitive to the model structure. The biogas yield of substrates varies, depending on the elemental and chemical composition, total and volatile solids, organic content, oxygen demand, carbon to nitrogen (C/N) ratio, and level of inhibitory substances [29]. Typically, fats and proteins generate increased CH<sub>4</sub> levels than carbohydrates, with compounds such as lignin not being degradable under anaerobic conditions [33]. Biological oxygen demand (BOD) and COD are additional indicators of organic content in feedstocks and are both employed for predicting biogas production [4,34–36]. The optimal range of C/N ratio for gas production is 20–35:1 [36]. A low ratio indicates elevated proteomic content, resulting in exacerbated ammonia levels and eventual methanogenic inhibition, while high ratios lead to reduced gas production due to nitrogen depletion [37].

### 4. Materials and Methodology

#### 4.1. BMP Prediction Model: A Stochiometric Approach

The theoretical prediction of BMP was determined using an R-based software package (Process Biogas Data and Predict Biogas Production) developed by Hafner et al. [38]. The model predictions and calculations are based on the theoretical stoichiometry of biomethanation reactions described by Rittmann and McCarty [39] and cited by Hafner and Rennuit [40]. The reactions are as follows:

$$C_{n}H_{a}O_{b}N_{c} + \left(2n + c - b - \frac{9df_{s}}{20} - \frac{9f_{e}}{4}\right)H_{2}O \rightarrow$$

$$\frac{df_{e}}{8}CH_{4} + \left(n - c - \frac{df_{s}}{5} - \frac{df_{e}}{8}\right)CO_{2} + \frac{df_{s}}{20}C_{5}H_{7}O_{2}N +$$

$$\left(c - \frac{df_{s}}{20}\right)NH_{4}^{+} + \left(c - \frac{df_{s}}{20}\right)HCO_{3}^{-}$$

$$f_{s} = f_{s}^{0}\left(\frac{1 + (1 - f_{bd})b\theta_{x}}{1 + b\theta_{x}}\right)$$

where  $f_s$  is the substrate electrons going to the cell synthesis (fraction);  $f_e$  is the substrate electrons going for energy production (fraction); d = 4n + a - 2b - 3c (dimensionless);  $f_s^0$  is a constant – intrinsic value (dimensionless);  $f_{bd}$  is the degradability of microbial biomass (fraction);  $\theta_x$  is the solids retention time (d) and b is the rate of microbial biomass decay (d<sup>-1</sup>).

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Within this model, biomethane prediction is expressed in mL at standard conditions of 101.325 kPa (1.0 atm) and 0 °C (273.15 K). Additionally, the model predicts total inorganic carbon, including both  $CO_2$  and  $HCO_3^-$ , ammonia consumption/production, and cell biomass production [40]. Theoretical BMP estimation assumes that organic matter (substrate) is completely biodegraded to  $CH_4$  and  $CO_2$ , where cell synthesis  $f_s$  is zero ( $f_e = 1$ ). The model allows the user to correct the prediction estimate to account for cell synthesis  $f_s$ . Complex substrates, such as sludge and other types of mixed wastes, are not completely degraded during AD, thus the degraded fraction level can be specified within the model. COD loading can also be used to calculate  $CH_4$  production, based on the oxidation of  $CH_4$  with  $O_2$  [39]:

$$\frac{1}{8}CH_4 + \frac{1}{4}O_2 \rightarrow \frac{1}{8}CO_2 + \frac{1}{4}H_2O$$

#### 4.2. Materials

#### 4.2.1. Municipal Wastewater Data of GCC States

The volume and chemical composition of wastewater sludge generation within the GCC region are not publicly available. Consequently, estimation of the biomethane production from sludge was not feasible at the time of execution of this study. Alternatively, the annual COD loading was utilized as a parameter to estimate  $CH_4$  production. The COD loading was calculated using the annual wastewater influent and COD concentration for each country (Table 2). The wastewater COD concentration for Bahrain was not available at the time of this study. However, the influent represents 3% of the total influent wastewater within the GCC. The BOD/COD ratio is an indicator of the biodegradable fraction of wastewater (Table 2). One of the major limitations for employing COD is that the model only estimates the theoretical biochemical  $CH_4$  potential, though not fugitive  $CO_2$  [38]. Through the use of additional parameters, such as the elemental composition (C, C, C, C, C, C), this model can also predict  $CC_2$  partitioning and total biogas production. Since the elemental composition and volume of sludge datasets were not available for all GCC states excluding Kuwait, the latter member state was used as a reference case to estimate total biogas production through assessment of elemental compositions of wastewater sludge.

	Wastewater Influent 2019 (10 <sup>6</sup> m <sup>3</sup> /year) <sup>a</sup>	COD Influent mg/L	COD Effluent mg/L	BOD/COD	COD Loading 10 <sup>3</sup> Tonnes
UAE	<i>77</i> 1	452 <sup>b</sup>	22 <sup>b</sup>	0.44 <sup>b</sup>	348
Bahrain	154	-	-	-	-
KSA	3083	533 <sup>c</sup>	24 <sup>c</sup>	0.60 <sup>c</sup>	1642
Oman	95	583 <sup>d</sup>	24 <sup>d</sup>	0.51 <sup>d</sup>	56
Qatar	278	441 <sup>e</sup>	-	$0.41~^{ m f}$	123 <sup>f</sup>
Kuwait	334	<b>442</b> g	<b>2</b> 9 <sup>g</sup>	0.46 <sup>g</sup>	147

Table 2. GCC wastewater characteristics.

a—[12], b—[41], c—[42], d—[43], e—[14], f—[44], g—[45].

# 4.2.2. Municipal Wastewater Data for Kuwait

Municipal and industrial wastewater is managed and treated by the Ministry of Public Works (MPW). The total wastewater collected in 2019 was  $378 \times 10^6$  m³—generated from residential, governmental, and commercial sectors [46]. There existed (in 2019) six wastewater treatment plants (WWTPs), where five plants operated using a three-phase system; primary, secondary, and tertiary (sand filtration and disinfection). The Sulaybia plant, which treats 53% of all wastewater reserves, includes an additional reverse osmosis (RO) and UV disinfectant treatment phase. The majority of effluent is distributed locally for reuse in irrigation, natural reserves, artificial ponds, injection wells, and other commercial uses. The wastewater treatment system generates approximately  $3.2 \times 10^6$  m³ of wet sludge annually [46], equivalent to 158,000 tonnes of dry sludge (assuming wet sludge

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has a 6%-solids content and a density that is similar to water at ambient temperature). Wet sludge is dewatered, solar dried, and stored on sight or landfilled. Previously, dry sludge was employed for agricultural purposes, but the Kuwait Environmental Protection Authority (KEPA) has recently banned this practice. Dry sludge samples were collected from the Sulaybia WWTP between October and December of 2020, and analyzed for physico-chemical characteristics (Table 3).

Parameter	Mean	Standard Deviation	Unit	
рН	6.42	0.4		
Moisture	7.1	0.5	%	
Ash	51.5	3.7	%	
Conductance	10,277	15.2	μmho/cm	
Alkalinity	818	43.1	mg/L	
T.O.C	201,719	14,666	μg/g	
T.C	236,096	36,938	μg/g	
Carbon	24.2	3	% d.m.	
Hydrogen	4.6	0.9	% d.m.	
Öxygen	14.8	2.4	% d.m	
Nitrogen	4.2	0.5	% d.m.	
Sulfur	0.9	0.08	% d.m.	
C/N	6.5			
Calcium	27,560	210	mg/Kg	
Copper	389	15	mg/Kg	
Iron	14,600	511	mg/Kg	
Manganese	9694	377	mg/Kg	
Zinc	826	20	mg/Kg	
C.O.D	6695	203.9	mg/Kg	
H.H.V	9.4	0.8	MJ/Kg	
Empirical formula *	$C_7H_{15}O_3N$			
Mass	$158 \times 10^3$		Tonne/year	

<sup>\*</sup> The empirical formula was calculated using a mass composition (C,H,O,N) data approach.

#### 4.3. Model Inputs, Assumptions, and Limitations

Biogas production estimates were based on the latest available data on GCC wastewater and sludge generation rates. Estimation of the expected growth of biogas production, based on future wastewater and sludge generation rates, was beyond the scope of this study due to the lack of such data. The COD loading rates for each country are presented in Table 2. The COD removal efficacy was, in its near entirety, based on the influent and effluent COD concentration. The BOD/COD ratio served as the biodegradable fraction of wastewater  $(f_d)$ . The fraction of substrate that was used for cell synthesis  $(f_s)$  ranged between 5-25%, a midpoint value of 15% was used in the model [40]. For Kuwait's reference case, 158,000 tonnes of dry sludge are produced annually. The AD was assumed to operate at the conventional temperatures range of 30–40 °C (mesophilic temperatures range) with an optimal pH range (6.5–8) [28,47]. The biodegradability of sludge was not analyzed in this study, though it was assumed to be 20.2% [48]. The total volume of biogas was impacted by the partitioning CO<sub>2</sub> in the aqueous and gas phase (biogas). Although  $CH_4$  has low water solubility, a significant portion of  $CO_2$  typically remains in solution [40]. The partitioning of CO<sub>2</sub> (i.e., composition of biogas) is also affected by temperature and pH of the final solution.

It is worth noting that biomethane estimates, which are based on COD loading data, were expected to be overestimated since the COD method does not account for energy expenditure on cell synthesis, and this model consequently assumed that all carbon is converted to  $CH_4$  and  $CO_2$ . The model also assumed the COD of  $CH_4$  to be 64 g of  $O_2$ /mole of  $CH_4$ , regardless of substrate. Additionally, the C/N ratio of the sludge was 6.48:1 which

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is sub-optimal for AD as the optimal range of C/N ratio for gas production is 20–35:1 [36]. Consequently, the biomethane production rates (which are based on COD loadings) are considered as the theoretical upper limits for biomethane production. Estimation of electrical power was based on a CHP engine with 45% efficiency and a biomethane energy content of  $11.04 \, \text{kwh/m}^3$ . The reverse osmosis (RO) energy requirement was  $5.5 \, \text{kwh/m}^3$  for desalinating seawater and was calculated using Kuwait's RO performance data and applied to the other GCC states.

The estimated biomethane production level for the region is based on the assumption that all the produced sludge from the wastewater plants is collected and anaerobically digested and does not take into account other waste streams such as municipal and agricultural wastes, the economic feasibility—which varies by location, plant size, and market conditions within each member state. Additionally, the CH<sub>4</sub> yields are based on average and aggregated wastewater data obtained from selected locations and assumes uniformity across plants and operational conditions.

#### 4.4. Estimating GHG Emission Reduction

The utilization of biogas and biomethane as an energy source can achieve emissions reduction by replacing conventional fossil fuels and avoiding fugitive CH<sub>4</sub> and CO<sub>2</sub> emissions, resulting from anaerobic decomposition of sludge in landfills/storage facilities. The annual emission reductions were calculated for Kuwait as a reference case, due the availability of sludge data and composition. Fuel displacements were based on the total heat content of potential biomethane, such that the annual expected heat energy from biomethane was converted into equivalent volumes of natural gas, crude oil, gas oil, and heavy fuel oil (HFO). The emissions and fuel volumes were based on the emission factors and heat content reported by the US Environmental Protection Agency [49]. Emissions from sludge disposal were based on the assumption that dry sludge undergoes anaerobic decomposition in a landfill, with similar performance to an anaerobic digestor. Consequently, CH<sub>4</sub> and CO<sub>2</sub> emissions from dry sludge disposal in a landfill are similar to those estimated by the AD model. This study compared two emissions scenarios; a base scenario where electricity is produced from conventional fuels and wastewater sludge is stored or disposed of in a landfill. The alternative scenario is where sludge is anaerobically converted into biogas and utilized as an energy source to produce electricity.

#### 5. Results and Discussions

# 5.1. BMP for the GCC Region

Table 4 shows a comparison between the biomethane prediction per gram of COD loading and wastewater dry sludge. The results indicated that estimation of BMP using COD loading yielded 144 mL/g of COD, which is nearly 30% more than the volume of BMP estimated using the elemental composition of dry wastewater sludge. Variations in estimations can be attributed to the factors discussed in Section 4.3, such as cell synthesis, biodegradability, C/N ratio, and the model's simplifying assumption that all carbon content in COD is converted to CH<sub>4</sub> and CO<sub>2</sub>. While the model estimations are based on stoichiometric ratios of input/output, it does not estimate the CO<sub>2</sub> volume when COD is used since it does not distinguish between the partitioning CO<sub>2</sub> in the aqueous and gas phase (biogas). Consequently, additional inputs such as temperature, pH, and composition were employed to estimate the total biogas volume (CH<sub>4</sub> and CO<sub>2</sub>) (Table 4). The empirical formula for dry sludge yielded a mean biogas volume of 139.5 mL/g, consisting of 72% biomethane and 28% CO<sub>2</sub> (Table 4). A literature review of the experimental BMP of wastewater sludge revealed that CH<sub>4</sub> yields vary greatly, from 50 mL/g to >1000 mL/g of sludge. These variations can be attributed to the type of sludge (primary, activated, or mixed), operating conditions (temperature and pH), organic loading rates, pre-treatment of sludge, and reactor of experimental setup [16,22,26,27,29,50–56].

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**Table 4.** Biogas production per gram of COD and sludge (substrate) at standard conditions at  $0 \,^{\circ}$ C and 1.0 atm.

	CH <sub>4</sub> (mL/g)	CO <sub>2</sub> (mL/g)	Biogas (mL/g)	CO <sub>2</sub> (g/g)
COD	144.33	-	-	-
$C_7H_{15}O_3N$	100.2	39.3	139.5	0.09

Table 5 presents the BMP of wastewater sludge produced in the GCC region. These estimates are based on the values in Table 4 and on the assumption that the chemical composition for sludge produced in GCC states is similar to that produced in Kuwait. Thus, the BMP estimated from the chemical composition was 30% less than the BMP estimated from COD loading. The biomethane potential of sludge for the entire region ranged between  $232-334 \times 10^6$  m<sup>3</sup> of biomethane (Table 5), with a total heat value up to 10.7 trillion BTUs annually. The lower end was BMP estimated from the chemical composition and the upper end was BMP estimated using COD loading. Saudi Arabia, the largest and most populated member state in the GCC, accounted for nearly 71% of all biomethane production, followed by the UAE at 15%. The remaining four counties accounted for 14% of all BMP. In its raw form, biogas can be utilized directly as a cooking fuel, fed to CHP plants, or can be upgraded to biomethane, to be injected into the gas grid for consumption by power plants. Biomethane production in the GCC region can generate up to 1665 GWh of electrical energy annually (Table 6), an amount equivalent to the current electricity generation from combined wind and solar energy sources. Regarding individual GCC member states, the UAE could gain a 13–19% increase in renewable energy (electricity) production when utilizing biomethane, while KSA could gain up to 537% increased electricity production from renewable sources. Desalinated seawater could be generated from renewable energy sources if coupled with RO technologies. Hypothetically, if all biomethane is used to power RO desalination units, the potential production of low-carbon-footprint freshwater can be as high as  $302 \times 10^6$  m<sup>3</sup> annually (6% of all current desalinated water production) (Table 6).

Table 5. Biomethane estimates for GCC states.

	Wastewater Influent 2019 (10 <sup>6</sup> m <sup>3</sup> /Year)	COD Loading 10 <sup>3</sup> Tonne	CH <sub>4</sub> (10 <sup>3</sup> m <sup>3</sup> ) C <sub>7</sub> H <sub>15</sub> O <sub>14</sub> N	CH <sub>4</sub> (10 <sup>3</sup> m <sup>3</sup> ) COD
UAE	771	348	34,870	50,227
Bahrain	154	-	-	-
KSA	3083	1642	164,528	236,991
Oman	95	56	5611	8083
Qatar	278	123	12,325	17,753
Kuwait	334	147	14,729	21,217
Total	4715	2316	232,063	334,268

Table 6. Electrical power and desalinated water production from Biomethane.

	Electricity Generation (GWh)			Freshwater Production (10 <sup>6</sup> m <sup>3</sup> )		
_	Electricity From CH <sub>4</sub>	Current Renewables	Percent Increase from CH <sub>4</sub>	Freshwater From CH <sub>4</sub>	Percent Increase from CH <sub>4</sub>	
UAE	172-250	1315	13-19%	31–45	4–6%	
Bahrain	0	9	0%	0		
KSA	812-1177	219	373-537%	148-214	5–7%	
Oman	27-40	16	175-276%	4–8	5–8%	
Oatar	61–88	123	50-72%	11–16	4–6%	
Kuwait	50-105	88	88–120%	13-19	4–6%	
Total	1152–1665	1770		150–302		

As the GCC states aim to increase the share of renewable sources (wind and solar) within the electricity sector, additional power flexibility is required to offset fluctuating

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wind and solar-based power production. Unlike the variable solar and wind-based energy production sources, biomethane can be directly utilized in gas turbines that can be dispatched in a timely matter to facilitate the integration of a high share of intermittent renewables. One key advantage of biomethane is that it can exploit existing natural gas infrastructures, such pipelines, storage and turbines.

#### 5.2. BMP for Kuwait and the Potential Emission Reduction

The estimated biogas composition for this study was 72% biomethane and 28% CO $_2$  by volume (Table 4). Annual dry sludge production in Kuwait is approximately 158,000 tonnes, which yields a BMP of 14.7  $\times$  10 $^6$  m $^3$ , with a total heat content of 471.7 billion BTUs. Biomethane could displace 13  $\times$  10 $^6$  m $^3$  of natural gas, or approximately 86,000 barrels of crude oil or other liquid fuels annually (Table 7). The decision on which fuel to displace depends on economic and environmental factors which capture the scarcity, energy security, and environmental facets of such fuels. Kuwait exports crude oil and, consequently, displacing crude oil would increase export capacity for the country, while displacing HFO would yield in maximum emissions reductions. The findings of this case study are meant to demonstrate the fuel savings and emission reductions of utilizing biogas as a clean and renewable fuel. While data on sewage and wastewater sludge were not available for the other GCC states at the time of this study, such potential benefits can be extrapolated to other GCC states since they all have similar fossil fuel powered plants.

Table 7. BMP for Kuwait and the volumes fossil fuel displacements annually.

	Value	Unit
Biomethane	14,729	$10^3 \text{ m}^3$
Heat content	471,770	mmBTU
	Fuels volumes with equivalent energy co	ntent
Natural Gas	12,965	$10^{3} \text{ m}^{3}$
Crude oil	86,619	bbl
Gas Oil	87,885	bbl
HFO	84,838	bbl

Two emissions scenarios were compared for this case study (Table 8). The base scenario was where electricity is produced from estimated fossil fuels and the dry sludge is stored or disposed of in a landfill. The alternative scenario was where sludge is anaerobically converted to biogas and utilized as an energy source to produce electricity. It is worth noting that emissions from sludge disposal were based on the assumption that dry sludge undergoes anaerobic decomposition in a landfill, with similar performance to an anaerobic digestor. Regarding the base scenario, the combustion of fossil fuels emits CO<sub>2</sub>, NO<sub>X</sub>, and CH<sub>4</sub>. Additionally, dry sludge emits CH<sub>4</sub> and CO<sub>2</sub> under anaerobic conditions. In this scenario, the combustion of natural gas emission emits roughly  $25 \times 10^6$  Kg of CO<sub>2</sub> annually, while the other liquid fuels emit  $35-38 \times 10^6$  Kg of CO<sub>2</sub> annually. Sludge disposal emissions in this scenario were  $9.6 \times 10^6$  Kg and  $13 \times 10^6$  of CH<sub>4</sub> and CO<sub>2</sub>, respectively. The total GHG emissions in this scenario ranged from 280,000-293,000 tonnes of CO<sub>2</sub> equivalents. In the alternative scenario, dry sludge underwent AD in a reactor where CH<sub>4</sub> is captured and used to as a substitute to fossil fuels. The combustion of biomethane emits  $CO_2$  and  $NO_X$ . Note that no carbon capture was assumed in either scenarios, rather  $CO_2$ was assumed to be released into the atmosphere. All emissions were converted into CO<sub>2</sub> equivalents and reported as GHG emissions (Table 8). The employment of biomethane as a clean, renewable fuel and the displacement of fossil fuels could potentially reduce GHG emission by 86% when compared to the base scenario (Table 8). The substantial reduction in GHG emissions is due to biomethane capture, which has  $25 \times$  fold increased global warming potential than CO<sub>2</sub>, that would otherwise be released from landfills into the atmosphere.

г 1	Combustion Emissions (kg)		Sludge Disposal Emission (kg)		<b>Total GHG Emissions</b>	
Fuel	CO <sub>2</sub>	NOx	CH <sub>4</sub>	CH <sub>4</sub>	CO <sub>2</sub>	(M.T CO <sub>2</sub> Equivalent)
		Base scenario	: Hydrocarbon co	mbustion + sludge d	isposal	
Natural Gas	25,032,116	47	342	O	1	280,218
Crude oil	35,637,506	283	1026	0.677.211	12 220 000	290,918
Gas Oil	35,345,008	283	1026	9,677,211	13,230,000	290,625
HFO	38,175,628	283	1026			293,456
	, ,,	Alterna	ative scenario: Bio	omethane combustion	ı	,
Biomethane	26.128.469	283	0	0	13,230,000	39.443

**Table 8.** Emissions comparison between using fossil fuels and biomethane in Kuwait's power plants.

#### 5.3. Pre-Treatment, Co-Digestion, and Biogas Upgrade

Biomethane yields from sludge AD are low when compared to other types of biomass, due to the presence of complex organic structures, microbial flocs (activated sludge), and other inhibitory compounds. However, the pre-treatment of sludge prior to AD can improve biodegradability of sludge and increases CH<sub>4</sub> production [28,57]. Further improvements can be achieved through co-digestion of sludge to adjust moisture content, C/N ratio and nutrient balance [28]. Co-digestion of sludge with lipids, such as fatty wastewater, meat processing by-products, food waste and organic municipal solid waste, can increase CH<sub>4</sub> production [28]. In addition to enhanced biomethane yield, co-digestion allows the cost sharing of various waste streams in a single digestor. However, the main drawbacks of co-digestion are the transportation costs and feedstock inconsistencies. Biogas can be valorized further by transforming it into enriched biomethane (natural gas), which has a higher market value and can be used by power plants, industry and households. Typically, the composition of biogas is 50–75% CH<sub>4</sub>, 25–50% CO<sub>2</sub> and other impurities. The utilization of raw biogas as a direct natural gas substitute (up to 95% CH<sub>4</sub>) is limited due to the potential corrosion of pipelines in the gas grid and inconsistencies in the calorific value of biogas. Thus, the purification and upgrading of biogas to biomethane are necessary for the removal of CO<sub>2</sub> and other impurities. Purification and upgrading technologies are based on adsorption and absorption principles, or separation by membranes [5,58,59].

#### 5.4. Barriers, Drivers and Policies Regarding Biomethane Deployment

Despite the huge potential for biomethane in the GCC region, the deployment of biogas and biomethane recovery and utilization is hindered by several barriers which can be summarized into technical, economic, and policy barriers. Infrastructural challenges such as the lack of pipelines and connections from wastewater plants to the national gas grid are major challenges. Additionally, the co-digestion of sludge would require an appropriate waste management system for the collection, segregation and storage of waste, all of which are under-developed waste management options in the GCC region. The composition of biogas varies according to the operating parameters (including temperature, retention time, input rate) and consequently creating inconsistent heat content of biogas across differing biogas plants or seasonal variations. The investment costs of biogas installations and the lack of economic incentives create further barriers to the deployment of biomethane as a source of energy. The construction and equipment costs, along with the treatment and transportation of biomass, can negatively impact the budget of a biogas plant. A study by Fraunhofer ISE, ref. [60] compared the costs of various renewable energy technologies in Germany using the levelized cost of electricity (LCOE), given differing plant capacities, life spans and capital costs. The study found that the LCOE of biogas plants remains higher than wind and solar PV installations, where the LCOE of biogas is 10.17–14.74 €<sub>cents</sub>/kwh while wind and solar PV costs were 3.71–13.79 €<sub>cents</sub>/kwh. In addition, the lack of government invectives such as financial support and loans render biogas projects less attractive to investors and this contributes to the low adoption rate of biogas technologies. In order to promote biogas deployment and recovery, several economic incentives can be applied to offset the high investment costs and provide other revenue streams to the WWTP or biogas facility. Feed-in tariffs for electricity generated from biogas, together with subsidies for using feedstocks, such as wastewater sludge or other forms

of biomass, can incentivize the deployment of biogas technologies. Additionally, carbon credits and trading can provide an alternative revenue stream for biogas facilities, as biogas recovery avoids potential  $CH_4$  emissions from landfills and displaces fossil fuels.

A sustainable deployment of biogas recovery from wastewater sludge is dependent on policies regarding the water, energy, and environmental sectors. Recovered biogas from AD in WWTPs is a renewable source of energy and is a substitute to natural gas in its upgraded form (biomethane). Thus, renewable energy targets requiring a fraction of the energy mix to be met with biogas, can promote the generation of a considerable volume of renewable biomethane in the GCC region from wastewater sludge and other organic waste. Emission reduction targets for the wastewater plants and power generation plants can help in further adoption of biogas recovery by avoiding the emission of CH4 into the atmosphere and the displacement of fossil fuels for power generation. Additionally, landfill disposal regulations can be imposed on the organic fraction of municipal solid waste to incentivize the collection and treatment of organic waste as a co-digestion substrate.

#### 6. Conclusions and Future Work

The findings of this study demonstrate the vital role of biogas and biomethane as a renewable fuel in decarbonizing the energy and water systems within the GCC region, together with highlighting the importance of diverting organic substrates from landfills to avoid CH<sub>4</sub> release. The biomethane potential of sludge for the region ranges between  $232-334 \times 10^6$  m<sup>3</sup>, with a total heat-value up to 10.7 trillion BTUs annually. The produced biomethane can generate up to 1665 GWh of electric energy, an equivalent amount to the current levels of electricity generation from wind and solar power combined. The findings from the case study on Kuwait's indicate that biomethane could displace  $13 \times 10^6$  m<sup>3</sup> of natural gas, or approximately 86,000 barrels of crude oil, together with reducing greenhouse gas emissions by 86% when compared to the base-scenario. In addition, biomethane can serve as a flexible and renewable source of energy to maintain a reliable power supply with minimum carbon emissions, allowing larger shares of variable energy sources (wind and solar) to be integrated into the power systems. Despite its benefits, the widespread deployment of biogas generation and recovery from organic substrates in the GCC region is hindered by several economic and policy barriers. The fossil fuels production industries are mostly state owned and receive political and financial support from the governments in the region. Thus, low carbon energy targets, energy and environmental policies, and economic incentives remain the major drivers for deployment of the biogas and biomethane industries. The scope of this paper was limited to the theoretical estimation of biomethane potential, using publicly available data on wastewater, sludge characteristics and chemical composition. Further research is required on biomethane potential using experimental methods which mimic anaerobic conditions in practice and assess the impact of operational factors (such as biodegradability, incubation times, macronutrients requirements, and temperature) on CH<sub>4</sub> yields.

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#### **Abbreviations**

BMP Biochemical methane potential
 BOD Biological oxygen demand
 CHP Combined heat and power
 COD Chemical oxygen demand
 GCC Gulf Co-operation Council
 KEPA Kuwait Environmental Protection Authority
 MPW Ministry of Public Works

RO Reverse osmosis

Keverse osinosis

WWTP Wastewater treatment plant

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