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# Solar PV adoption in wastewater treatment plants: a review of practice in California

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# Abstract

This is the first study to assess the current status of solar photovoltaic (PV) adoption across different wastewater treatment plant scales, and to identify the opportunities for solar PV in the wastewater sector. It quantifies solar PV contributions to the energy demand of the wastewater sector and improves knowledge of sector-specific factors influencing PV uptake. California was used as a case study due to its high commitment to solar power and the high data availability. The study compiled and examined data on multiple wastewater treatment plant attributes from 105 Californian plants, representing 78% of total state flows. The analysis focused on the effect of three sector-specific influencing factors: size of wastewater treatment plant, presence/absence of anaerobic digestion and geographical location. Solar PV adoption critically depended on the size of the wastewater treatment plants. Of the 105 plants analysed, 41 installed a solar PV system. 40 of these 41 were installed in wastewater treatment plants with a flow rate below 59 mega gallons day$^{-1}$ (MGD). Above 59 MGD, solar PV was not installed unless specific circumstances occurred. In wastewater treatment plants with a flow rate above 5 MGD, solar PV was primarily installed in hybrid configurations with anaerobic digestion. In these plants, biogas contributed between 25% and 65% of the overall energy demand, while solar provided between 8% and 30%. In wastewater treatment plants with a flow rates below 5 MGD, solar PV often represented the only source of renewable energy, producing between 30% and 100% of the energy demand of these plants. Across all the plants analysed, 1 MW was the most adopted solar installation size and solar PV installations were mostly found in wastewater treatment plants in rural settings.
These results demonstrate the role that solar PV has in wastewater treatment plants in specific size range and geographic locations. This study contributes new, critical knowledge to the sustainable management of wastewater, and identifies future opportunities for the sector.

**Highlights:**

- Detailed review of solar PV uptake in wastewater treatment
- Identification of key influence of plant size in current solar PV use
- 1 MW is the most popular size of solar PV system installed
- In plants with flow rate above 5 MGD solar PV is installed with anaerobic digestion
- In plants below 5 MGD, solar PV is applied with and without anaerobic digestion

**Keywords:** renewable energy; solar photovoltaic; biogas; energy recovery; technology scaling; location

**List abbreviations and nomenclature with units**

WWTP = wastewater treatment plant
AD = anaerobic digestion
PV = photovoltaic
EPA = Environmental Protection Agency
EPRI = Electric Power Research Institute
NREL = National Renewable Energy Laboratory
IRENA = International Renewable Energy Agency
kW = kilowatt hour
GWh/year = gigawatt hours per year
kWh/MG = kilowatt hours per mega gallon
MGD = mega gallon per day
$m^3$/day = cubic meters per day

# 1.Introduction

On-site renewable energy generation has become increasingly common as part of the energy management strategies of urban wastewater treatment plants (Argaw, 2003; Tarallo, 2014). Wastewater treatment plants have used renewable energy generation to support the increasing energy demand associated with wastewater treatment, mitigating rising energy costs from the energy grid and associated greenhouse gas emissions (Mo & Zhang, 2012). Through the adoption of renewable energy sources, wastewater treatment plants have the ability to significantly reduce the overall energy demand (Mizuta & Shimada, 2010; MWRA, 2017), become energy self-sufficient (DeGarie, 2000; Gu *et al.*, 2017) and, in some cases, energy positive (Hanson, 2014; Wett *et al.*, 2007).

There are several sources for on-site renewable energy generation available to wastewater treatment plants. These sources are sector specific and non-sector specific. The sector specific sources refer to the energy recovery embedded in the wastewater, which includes biogas generation from anaerobic digestion of biosolids (Shen *et al.*, 2015), heat recovery from the wastewater (Funamizu *et al.*, 2001), energy recovery from the incineration of biosolids (Stillwell *et al.*, 2010), biofuel production (Seiple *et al.*, 2017) and hydropower generation. Non-sector specific sources instead include solar photovoltaic (PV) and wind (Helal *et al.*, 2013). Despite the variety of sources available to the sector, scientific research in this field has predominantly focused on sector specific sources, and in particular on biogas generation from biosolids. However, energy recovery from biogas is not always an economically viable option (EPA, 2011), limiting its applicability and leaving the sector with little information on alternative RE opportunities.

This lack of research is in contrast with the high interest shown by wastewater utilities in non-sector specific sources and in particular in solar (PV), as highlighted in recent sectoral studies in the US and Australia (Badruzzaman *et al.*, 2015; BECA, 2015). To date however, research on PV has focused on its theoretical feasibility and the economic viability in single wastewater treatment plants used as case studies. Foley (2010) analysed the economic feasibility of solar in a wastewater treatment plant in Singapore to meet the plant's energy requirement. He concluded that solar energy was economically viable only with a rebate of at least 63%. Mo and Zhang (2013), and Gu *et al.* (2017) instead indicated that solar PV has a great generation potential in wastewater treatment plants with the large land availability. Bustamante and Liao (2017) successfully combined solar PV with biogas in a hybrid configuration to achieve energy self-sufficiency in a high-strength wastewater treatment system. However, these works focus on specific plants and neither assess the conditions favourable to the adoption of solar PV at large scale nor provide a quantitative analysis of its adoption across the sector. Therefore, whilst there is growing interest in RE in the wastewater sector, there is a significant shortage of useful data to quantify the current opportunity of solar PV for the sector and how different factors affect its integration in wastewater treatment plants.

Several factors influence the decision of adopting solar PV in wastewater treatment plants (Sampaio & González, 2017). These factors can be grouped in four main categories: technical, economic, social and institutional (Ahlborg & Hammar, 2014; Kwan, 2012). Within each category, the factors are either *general* or *specific* to the wastewater treatment plants. The *general* factors refer to those characteristics affecting the installation of solar PV, regardless of the sector studied. Among them, are the solar irradiation and temperature, the presence of subsidies and incentive schemes, the initial costs and return on investment, the energy price and the energy market opportunities.

*General* factors have been widely studied in several contexts, countries and scale (e.g. household, commercial). Baranzini *et al.* (2017) and Silveira *et al.* (2013) showed the effect of social and economic factors on the adoption of solar at household, commercial and farm level, while Kim *et al.* (2014) and Njoh *et al.* (2019) studied the combination of factors driving the adoption in South Korea and Cameroon. Lang *et al.* (2016) proposed a techno-economic analysis of rooftop applications in the absence of subsidies. Walters *et al.* (2018) instead adopted a system approach to the study of the technical and non-technical factors influencing household solar adoption.

The *specific* factors refer to the unique characteristics of the wastewater treatment plants. The size and energy demand of the wastewater treatment plants, the presence of other renewable energy sources, and the space availability are among the main specific factors identified. Despite the considerable amount of work conducted on the *general* factors, to date the *specific* factors affecting solar adoption in the wastewater sector have not been investigated. Understanding under what circumstances these factors act as drivers for the adoption of solar PV can help the wastewater sector to take advantage of the benefits of its adoption.

Therefore, this study aims to compile a detailed review of current solar PV uptake in wastewater treatment plants and to improve the understanding of three *specific* factors for its current adoption. Specifically, this research analyses: i) the size effect of wastewater treatment plants, ii) the effect of the presence or absence of biogas in the plant and iii) the effect of the location of the wastewater treatment plant. The study uses California as a case-study of global practice because of its high commitment to solar power and the high data availability (EIA, 2016; State of California, 2007).

By analysing the energy data, size and geographic location of 105 Californian wastewater treatment plants, this research addresses five research questions:

- What is the current adoption of solar PV in the wastewater sector in California?
- How does the size of the wastewater treatment plants affect the size of the solar systems installed?
- How does the presence or absence of anaerobic digestion affect the adoption of solar PV in wastewater treatment plants?
- How does the location of the wastewater treatment plants and the space availability affect the adoption of solar PV in wastewater treatment plants?
- How much does solar PV contribute to the energy demand of the wastewater treatment plants compared to biogas?

The study provides, for the first time, a quantitative analysis of the solar energy generated from wastewater treatment plants and analyses some of the sector *specific* factors affecting solar PV adoption. This work contributes, therefore, to broader the understanding of the integration of renewable energy sources in the wastewater sector. It supports the sector in making informed decisions over RE investments, helping wastewater utilities to transition towards sustainable management practices.

# 2. Materials and Methods

Solar and biogas energy data, wastewater treatment flow rate and geographic location from 105 Californian wastewater treatment plants were compiled and analysed to determine the contribution of solar PV to the energy demand in the wastewater sector. The sample identification and energy data collection process consisted of five phases (Figure 1). The process commenced with the analysis of the wastewater sector and the solar PV market of the USA and led to the creation of a dataset of 105 wastewater treatment plants in California.

## 2.1. Sample identification and data collection process

### *2.1.1. Phase 1: Wastewater treatment plant characteristics and solar PV capacity in the USA*

The US became the focus of this study because of the large number of publicly available datasets on wastewater treatment plants, their characteristics and PV power generation. During *Phase 1,* three datasets on wastewater treatment plants and solar PV in the US were analysed to identify a suitable case study for this project. The two main datasets on wastewater were the Clean Watersheds Needs Survey (CWNS) (2012) and the Biogas Data (2015). The Clean Watersheds Needs Survey provided data on wastewater treatment plants divided by US states, including the flow rate of wastewater treated, the population served and the geographic location of each plant. The Biogas Data dataset instead provided the list of plants with installed anaerobic digestion (AD), regardless of the application of the biogas produced during the AD process.

Combining the information from these two datasets, it was possible to rank the US states based on the flow of wastewater treated and the wastewater flow treated with AD.
The third dataset used was the NREL Open PV Project (2018), which ranked the US states by their investment in solar PV.

These three datasets identified California as the target case study region. California was identified as the state with the highest volume of wastewater and with the highest proportion of that wastewater treated in wastewater treatment plants with AD. Also, California was the state leading the way in solar PV investments, having the highest installed capacity of 7379 MW (NREL, 2018).

### *2.1.2. Phase 2: Identify wastewater treatment plant with and without AD*

The total number of wastewater treatment plants in California with known wastewater flow (569 plants) were divided into two groups: wastewater treatment plants *with* AD and wastewater treatment plants *without* AD. The distinction between the two groups was made because this study aimed at understanding the relationship between AD and the adoption of solar PV. California had 134 plants with AD, treating 2860 MGD. The remaining 435 plants with no AD treated a remaining volume of 622 MGD (Table 1).

### *2.1.3. Phase 3: Wastewater treatment plant categorisation*

A representative subsample of wastewater treatment plants was selected. To identify the subsample, the plants were divided into three main flow rate categories: below 5 MGD, between 5 and 50 MGD, and above 50 MGD. This categorisation was performed to enable a more precise subsampling from each category in the next phase, and to ensure the subsample captured the broad spectrum of plants present in California. The three categories were chosen based on the categorisation performed by Shen *et al.* (2015) on biogas production in wastewater treatment plants in the USA.

### 2.1.4. Phase 4: Categorised subsampling based on AD adoption ratio

To assure a representative adoption of AD in the subsample, the ratio of the flow treated with AD over the total flow of wastewater was determined for each category (Table 1). Plants were then sampled from each category aiming to obtain a final subsample with a similar flow ratio of the category it was selected from.

This process led to the selection of a final sample count of 105 wastewater treatment plants, equivalent to 18% of the total 569 plants in California. The 105 plants treated a total flow rate of 2700 MGD, equivalent to 78% of the total Californian flow rate.

| Flow rate (MGD) | California Total Wastewater Treatment Plants | | | | | | | California Wastewater Treatment Plants Sub-Sample | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total flow (MGD) | | % of California Flow | | % AD by flow | N˚ of Plants | | Total flow (MGD) | | % of California Flow | | % AD by flow | N˚ of Plants | |
| | noAD | AD | noAD | AD | | noAD | AD | noAD | AD | noAD | AD | | noAD | AD |
| <5 | 234 | 125 | 6.7 | 3.6 | 35 | 412 | 50 | 28 | 20 | 0.8 | 0.6 | 42 | 35 | 10 |
| 5-50 | 304 | 871 | 8.7 | 25 | 74 | 22 | 72 | 182 | 522 | 5.2 | 15 | 74 | 10 | 37 |
| >50 | 84 | 1864 | 2.4 | 54 | 96 | 1 | 12 | 84 | 1864 | 2.4 | 54 | 96 | 1 | 12 |
| *Total* | *3481* | | - | | - | *569* | | *2700* | | - | | - | *105* | |

*Table 1: Summary of wastewater treatment plant characteristics for California and for the sub-sample of 105 plants used for this study divided in three flow rate categories. AD=presence of Anaerobic Digestion, no AD= absence of Anaerobic Digestion, N°=number of plants*

### 2.1.5. Phase 5: Energy data collection

The last phase of the process involved the collection of the energy data for each of the 105 plants identified. Three types of energy data were collected:

- The electricity demand of the wastewater treatment plant
- The presence or absence of solar PV installation at the plant, the size of the solar PV system installed (kW), and the electricity generated by the solar PV system (GWh/year) and
- The annual electricity generated from biogas (GWh/year).

When no information on the presence of AD or solar PV was available, the originally selected plant was discarded and a new one was selected, following the criteria of Phase 4 (Figure 1).

In this phase, information on the presence of anaerobic digestion with *co-digestion* was also recorded. Since co-digestion of organic feedstock with sewage sludge enhance the production of biogas, its presence could impact the adoption of solar PV. No energy data were however recorded for the energy generated from biogas from co-digestion, since they were not representative of the energy potential of the wastewater treatment plant itself.

Of the 105 wastewater treatment plants considered for this study, 77 had either AD or solar PV or both and energy data were collected for those. The remaining 28 plants had no solar PV or AD.

## 2.2. Data analysis

Once the data collection was completed, data were analysed to:

- Quantify the extent of solar PV adoption
- Quantify the amount of electricity produced from solar PV in comparison to the electricity generated from AD
- Establish a relationship between solar PV and AD adoption. Specifically, whether the presence or absence of AD had limited the adoption of solar PV
- Determine the effect of the geographic location on the adoption of solar PV. Wastewater treatment plants were geographically visualised to determine their position relative to *urban* and *rural* settings. Six urban settings were identified following the classification of “main urban areas” provided by the US Bureau of Statistics (2010). These six areas are the most populated areas in California. The wastewater treatment plants within those six areas were considered *urban*, the remaining plants were classified as belonging to *rural* settings.

## 2.3. Dataset sources and limitations

Several sources were used to acquire the energy dataset, like research papers, technical reports, project reports from solar installers, end of financial year utility reports, utility websites and fact sheets. When data from several sources disagreed, utilities were contacted directly to confirm the final datum. These occurred for 5 plants.

The energy data of interest were not always available for every single plant.

When the capacity of the solar PV plant was known, the solar PV energy output was calculated using the NREL PV Watts Calculator (2016). This approach was, however, not possible for the energy generated from biogas. Biogas usage cannot be calculated from generic wastewater treatment plant characteristics because its usage is closely linked to the energy management strategy of each single plant.

Energy data for the 105 wastewater treatment plants referred to different years because it was collected from an array of sources published in the last ten years. For each plant, it was therefore collected from the most recent information available. Flow rates are reported in Mega Gallon Per Day (MGD), similar to the sources used for this study. In the metric system, 1 MGD is equivalent to 3,785.4 cubic meters per day ($m^3$/day).

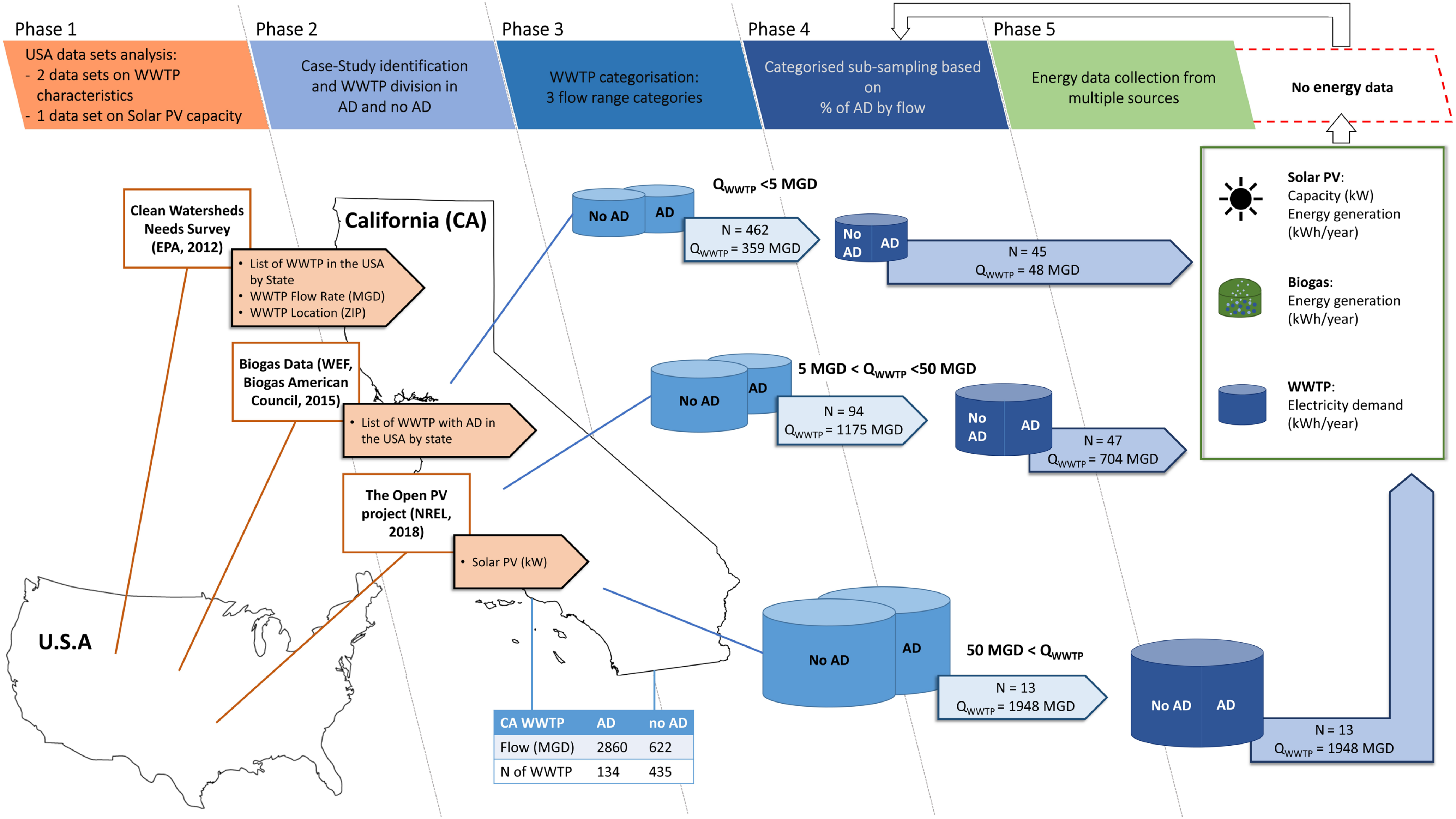
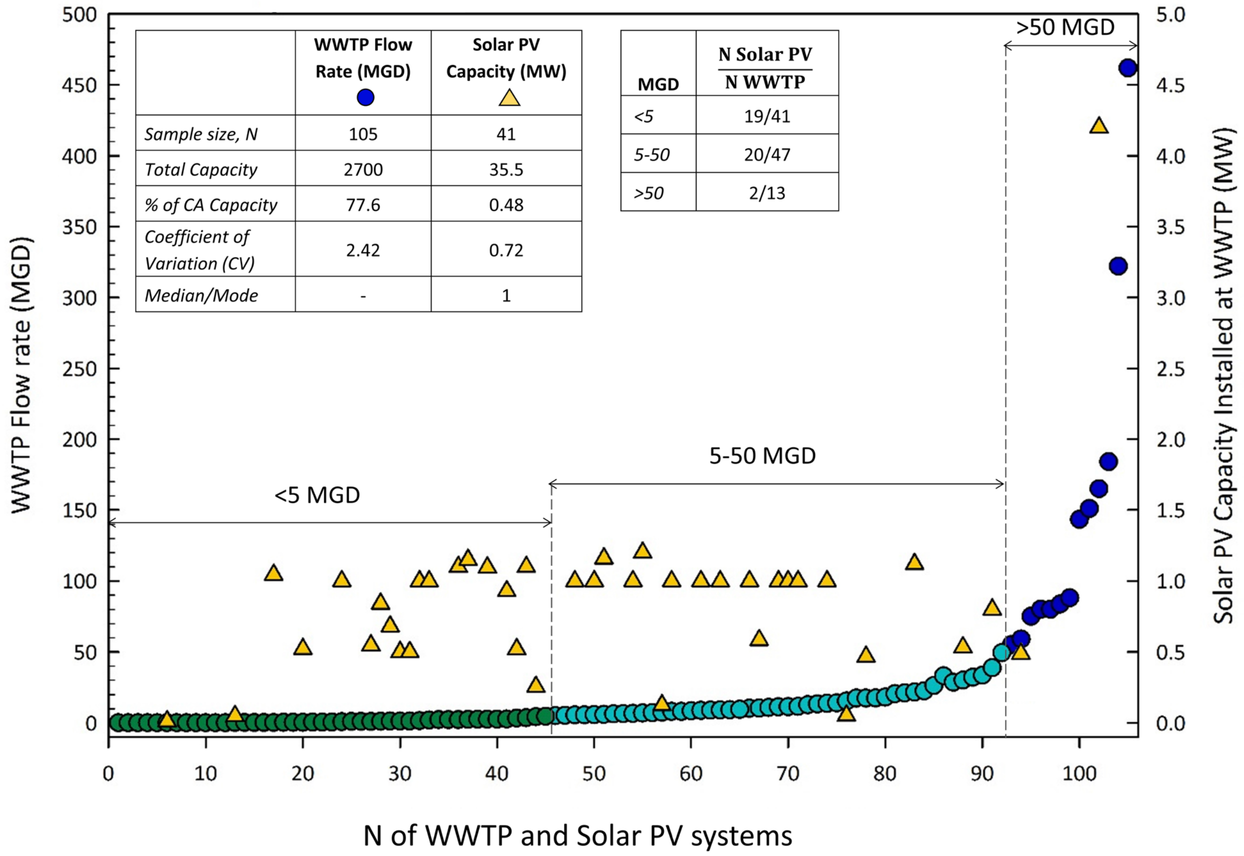



*Figure 1: Methodology flow chart. The chart shows the identification process for the sub-sample used in this study and the data collection process for each of the sample considered. Legend: $Q_{WWTP}$= WWTP flow rate (MGD), N= number of WWTP, AD=presence of Anaerobic Digestion, no AD= absence of Anaerobic digestion*

# 3. Results

## 3.1. Quantification of the Solar PV adoption




| | WWTP Flow Rate (MGD) | Solar PV Capacity (MW) |
|---|---|---|
| *Sample size, N* | 105 | 41 |
| *Total Capacity* | 2700 | 35.5 |
| *% of CA Capacity* | 77.6 | 0.48 |
| *Coefficient of Variation (CV)* | 2.42 | 0.72 |
| *Median/Mode* | - | 1 |

| MGD | N Solar PV / N WWTP |
|---|---|
| *<5* | 19/41 |
| *5-50* | 20/47 |
| *>50* | 2/13 |

*Figure 2: Representation of wastewater treatment plants (MGD-left y axis) and installed Solar PV capacity (MW-right y axis). Three flow rate categories are represented by the dots and each flow rate category is identified by a different colour. The solar PV capacity is reported as yellow triangles. WWTP= wastewater treatment plants*

There was no correlation between the size of the wastewater treatment plant and the size of the solar PV system installed (Figure 2).

The 41 solar PV systems installed at wastewater treatment plants ranged from a minimum capacity of 12 kW to a maximum of 4.2 MW, with an average installation of 0.86 MW. The most commonly installed Solar PV system was 1 MW, installed in 34% of the cases. Overall, the total solar PV capacity installed was 35.5 MW, which represented 0.48% of the total Solar PV capacity of California (NREL, 2018).

The solar PV systems were installed in wastewater treatment plants of different sizes, ranging from plants as little as 0.02 MGD to plants treating up to 165 MGD. 95% of the solar PV systems were installed at wastewater treatment plants below 50 MGD, with only two of the 13 wastewater treatment plants above 50 MGD adopting solar PV. Of the 39 installations in plants below 50 MGD, 19 were installed at wastewater treatment plants with a flow rate below 5 MGD, representing 46% of the total installations. The remaining 20 solar PV systems were installed at plants with a flow rate between 5 and 50 MGD, equivalent to 49% of the installations.

The wastewater treatment plant treating 165 MGD with a 4.2 MW solar system installed was the biggest plant with a solar PV installation. However, this plant presented unique conditions, which made it non-representative of global practices. The wastewater treatment plant was considered unique as it was surrounded by a buffer area used to separate the plant from the city. This area, bought in the 1970’s, provided the ideal space to install a large solar array (RegionalSan, 2016). This plant was therefore considered an outlier and 59 MGD was considered the biggest plant size with a solar PV installation representative of global practices.

## 3.2. The adoption of solar PV and the presence of anaerobic digestion

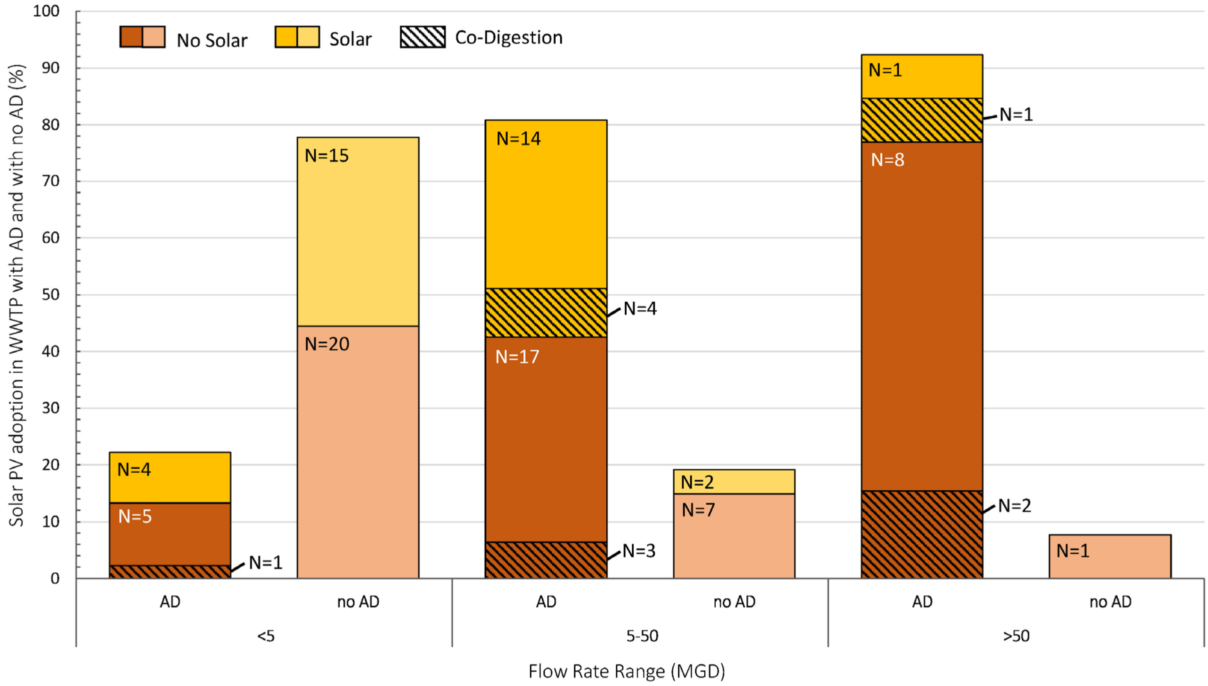



*Figure 3: Adoption of Solar PV in wastewater treatment plant (WWTP) with and without AD across three flow rate categories. Areas in dark and light yellow represent plants with solar PV while areas in dark and light brown represent plants without Solar PV. Areas with stripes represent plants with Co-Digestion. N reports the number of plants in each area.*

Solar PV and AD adoption rates vary with the wastewater treatment plant size (Figure 3). Anaerobic digestion (AD) was adopted in 22% of the wastewater treatment plants with a flow rate below 5 MGD. This percentage grew significantly to 81% in plants above 5 MGD, and 92% in plants with a flow rate above 50 MGD. Co-digestion was adopted in only 2% of the plants below 5 MGD, growing to an average of 15% in plants above 5 MGD.

In plants below 50 MGD solar PV was adopted in 42% of the plants but dropped to 15.4% in plants above 50 MGD.

In plants below 5 MGD, 79% of the solar PV systems were adopted in wastewater treatment plants without AD, while for wastewater treatment plants between 5 and 50 MGD, 90% of the plants with solar also had AD. In plants above 50 MGD no solar was installed in a plant without AD.

## 3.3. Effect of geographic location on the adoption of solar PV and anaerobic digestion

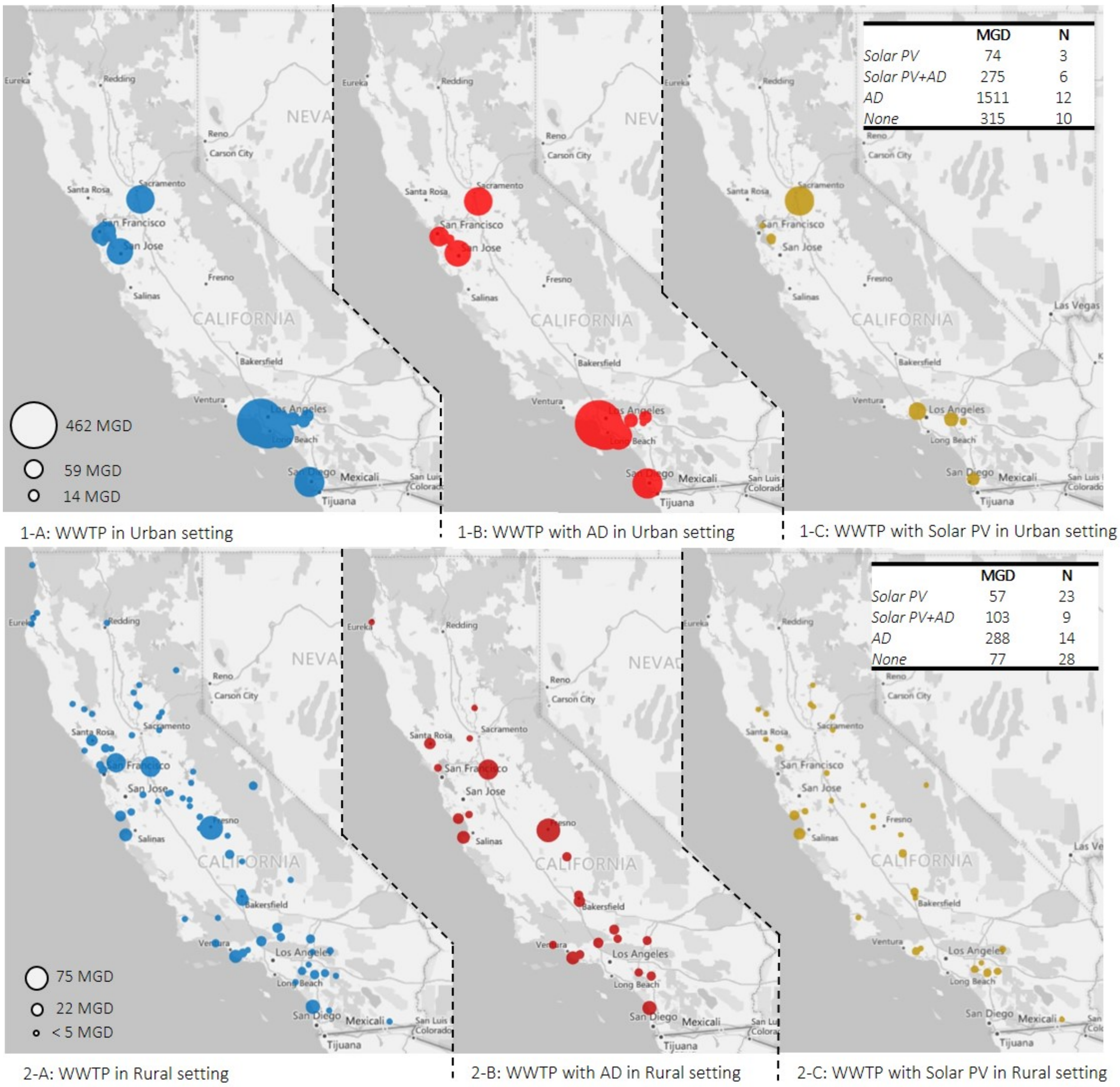



*Figure 4: Geographic distribution of wastewater treatment plant in California. At the top are reported the locations of the wastewater treatment plant (1-A), wastewater treatment plant with AD (1-B) and wastewater treatment plant with solar PV (1-C) in* urban *settings. On the bottom are reported the location of the wastewater treatment plant (2-A), wastewater treatment plant with AD (2-B) and wastewater treatment plant with solar PV (2-C) in* rural *settings. The size of the circles is proportional to the flow rate of the wastewater treatment plants.*

The 105 wastewater treatment plants examined in this study were located in 39 out of the 58 counties of California (Figure 4). 30% of the plants were located in the six main urban areas (Figure 4-1), while 70% were located in rural settings (Figure 4-2). Despite the higher number of plants in rural settings, the wastewater treatment plant in the main urban areas treated 80% of the total wastewater flow.

There was a slightly higher adoption of AD in rural settings, where 56% of AD systems were located. However, these plants treated only 18% of the total wastewater flow treated with AD. Therefore, the larger wastewater treatment plants with AD were located within the main urban areas. 78% of wastewater treatment plants with solar PV were in rural areas, treating 31% of the overall wastewater flow. Therefore, the smaller plants, hosting solar PV systems, were located in rural settings.

## 3.4. Contribution of solar PV to the electricity demand of wastewater treatment plant

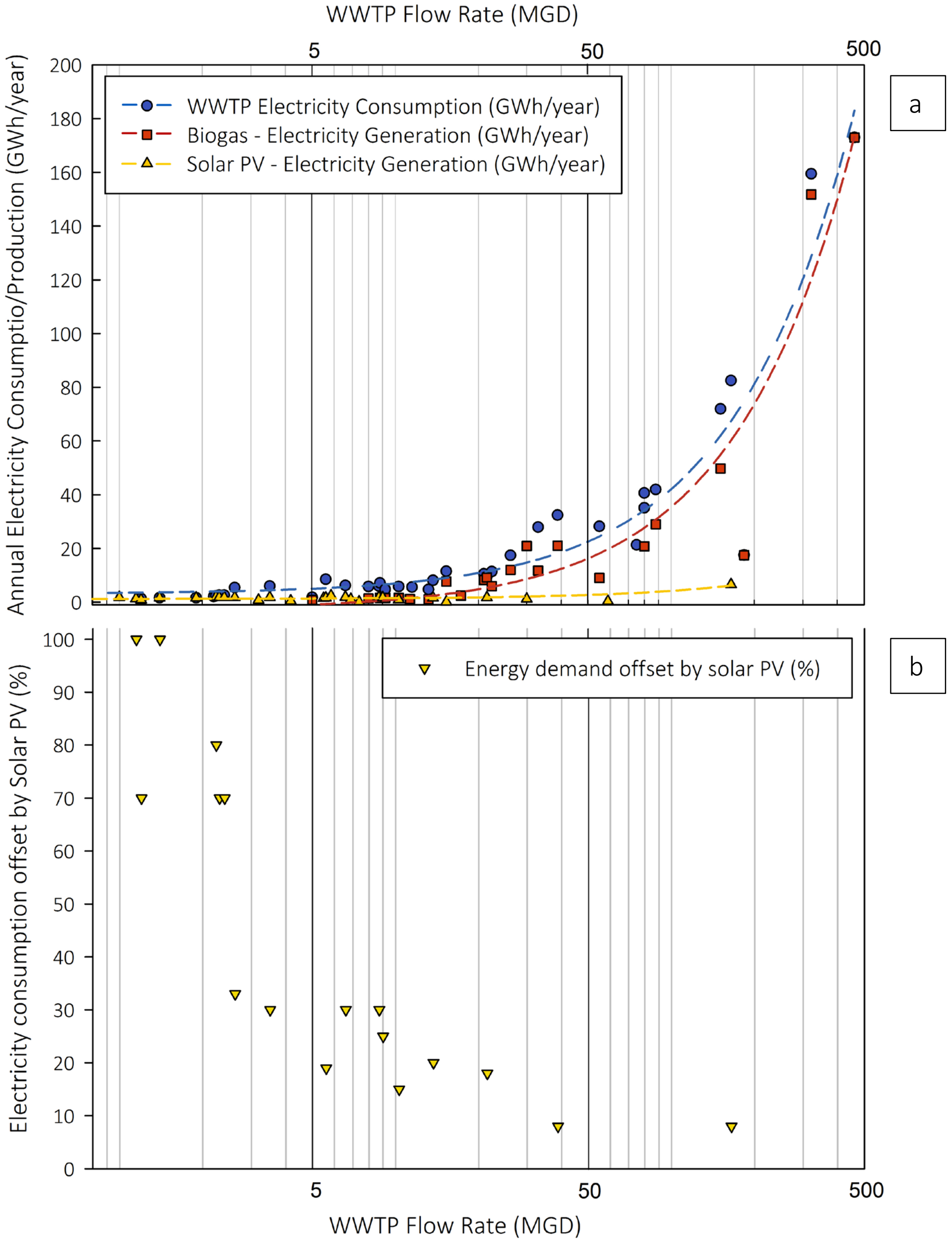



*Figure 5: [a] Comparison of the wastewater treatment plant electricity demand (blue dots and dashed line), electricity generation from biogas (red squared and red dashed line) and electricity generation from solar PV (yellow triangles and dashed line) (GWh/y). [b] Percentage of electricity demand of wastewater treatment plants offset by solar PV electricity generation (%).*

Solar PV electricity generation significantly offset the energy demand of wastewater treatment plants with a flow rate below 5 MGD (Figure 5-b), contributing between 30% and 100% of the electricity needs. Above 5 MGD, solar PV contributed between 8% and 30% of the electricity needs. Annual electricity demand of wastewater treatment plants grew with the increase in size of the wastewater treatment plants, ranging from 0.02 GWh/y to 173

GWh/y. The electricity produced from solar PV did not display the same growth, ranging from 0.02 GWh/y to 6.6 GWh/y (Figure 5-a).

The electricity generation from biogas followed the same trend as the energy demand, growing with the increase in size of the wastewater treatment plants and ranging from 0.79 GWh/y to 173 GWh/y (Figure 5-a). However, electricity from biogas was produced only in wastewater treatment plants above 5 MGD, making solar PV the only renewable energy source for wastewater treatment plants below 5 MGD. Six wastewater treatment plants above 5 MGD and below 50 MGD generated electricity from a combination of solar PV and biogas. Above 50 MGD, biogas was the main source of electricity, since only two plants had Solar PV.

In Figure 5-a, data on the electricity consumption were available for 40 wastewater treatment plants, while data for the electricity produced from biogas were available for 24 plants. Data on the electricity generated from solar PV were available for all 41 plants with solar PV, however the graph reports only information for plants with a flow rate above 1 MGD. With the data available it was possible to calculate the contribution of solar PV to the energy demand of wastewater treatment plant for 17 plants (Figure 5-b).

# 4. Discussion

## 4.1. Plant size and solar PV

This study highlighted the lack of correlation between the size of the wastewater treatment plant and the size of solar PV system installed, with the most popular size installed being a 1 MW solar array (Figure 2). Consequently, small plants tend to have solar systems that in some cases cover all of their energy needs, while larger plants have solar systems contributing less than 10%. (Figure 5-b). According to the 2017 California Energy Commission energy statistics, 1 MW is the most installed solar PV system among the 692 non-residential solar PV installations in California (California Government, 2017). Therefore, the solar PV adoption of 1 MW registered in the wastewater sector fits the trend of non-residential solar PV installation in the rest of California. This trend could have been influenced by the California Solar Initiative rebate scheme available for solar PV technologies of up to 1 MW (CPUC, 2016).

## 4.2. Solar PV in wastewater treatment plants below 5 MGD

Small wastewater treatment plants have higher specific power consumption (kWh/MG) than larger plants (Mizuta & Shimada, 2010), making them more sensitive to increases in energy price. It is therefore more important for small plants to find alternative energy sources to increase resilience to the energy cost fluctuations. Solar PV represents a suitable source of energy for small wastewater treatment plants for two main reasons: lack of biogas recovery opportunity and land availability.

The EPA (2007) noted that for wastewater treatment plants with less than 5 MGD flow, it is not cost effective to recover biogas for energy applications. This is confirmed by this study, for which no plant with AD recovered biogas for electricity purposes (Figure 5), except for Millbrae wastewater treatment plant, which invested in kitchen grease co-digestion technology, increasing its biogas generation to a cost-effective volume (Nastu, 2006). The economic barrier to the recovery of the embedded energy in the influent wastewater has turned the sector towards non-sector specific renewable energy sources, with nearly half of the small wastewater treatment plants analysed in this study installing a solar PV system.

Plants below 5 MGD are often located in rural areas, with generally more land availability (Figure 4). The rural settings therefore offer greater opportunity for solar installation, which requires land. The most common applications for solar PV are ground mounted, found in both fixed and tracking variation. However, since 2015 small pond treatment systems have shown a growing interest for floating solar PV array installations. Jamestown, in South Australia (BECA, 2015; Hamden, 2016), has successfully tested one of the first floating systems. The same design was successfully implemented in 2016 in Holtville wastewater treatment plant, California (InfratechIndustries, 2015).

Despite the higher specific power consumption, small wastewater treatment plants have an annual energy consumption that can be offset with Solar PV without needing prohibitively large areas of land. The current solar PV adoption can offset between 30% to 100% of the energy needs of small wastewater treatment plants with an approximate land requirement of 20,000 $m^2$ (5 acres). The combination of the pressure of the energy price, lack of biogas opportunities, and the space availability, make solar PV an appealing option for small wastewater treatment plants.

### 4.3. Solar PV in wastewater treatment plants between 5 and 50 MGD

Almost half of the wastewater treatment plants with a flow rate of 5-50 MGD have a solar PV system installed, while 80% recover biogas for energy use. In these plants, solar PV contributed between 8% and 30% to the energy demand, while biogas met between 25% and 65% of the energy demand (Figure 5-a). The energy generated from biogas depended on the size of the plant, the treatment level and the technology adopted to generate electricity from biogas. These results demonstrated that in wastewater treatment plants within the size range considered, neither solar PV, nor biogas alone, are therefore sufficient to cover the energy needs.

As a strategy to increase energy generation, co-digestion had a relatively low adoption, with only 15% of the plants adopting this technology to increase the biogas production (Figure 3). As summarised by Shen *et al.* (2015), this low adoption rate can be explained by numerous technical and economic challenges that are currently preventing the systematic adoption of co-digestion. This trend is in line with the low adoption of co-digestion in the US, which has been estimated to be approximately 17% (WEF, 2013).

The pairing of biogas generation with solar PV was adopted in 38% of the plants. While in plants below 5 MGD the presence/absence of AD did not influence the adoption of solar, in plants between 5 and 50 MGD the presence of biogas generation seemed to support the adoption of solar PV. Almost half of the plants with AD had a solar system installed, while only 22% of the plants without AD invested in solar PV (Figure 3). The preference toward hybrid solar PV-biogas systems can be explained by the greater energy management flexibility provided by these systems (Erdinc & Uzunoglu, 2012; Helal *et al.*, 2013). For example, the complementary use of the two technologies can guarantee energy generation 24 hours per day, as plant managers can decide to burn biogas at night, when no solar power is available. The combined use of the two technologies may therefore play a key role in enabling medium sized wastewater treatment plants to comply with air regulations (ARB, 2017; Carreras-Sospedra *et al.*, 2016). The potential of hybrid solar PV-biogas systems has been proven by Helal (2013) and Halaby (2017). In these studies, the authors estimated that by using a hybrid power system, combining heat and power system, solar PV and wind power, could reduce GHG emissions by 83% compared to power from the grid. Even though hybrid power systems provide substantial advantages, their implementation is expensive and requires solutions designed around the specific characteristics of each individual site (Chae & Kang, 2013).

### 4.4. Solar PV in wastewater treatment plants above 50 MGD

Only two of the 14 wastewater treatment plants above 50 MGD installed solar PV. This probably reflects the limited potential contribution of solar PV to the energy demand, and the high land space requirement for the installation of bigger solar PV systems. Solar PV systems of 1 MW would be in fact able to contribute only 1-6 % of the energy demand of large wastewater treatment plants (Figure 5-a).

The two plants above 50 MGD with a solar PV installation were the D.C. Tillman water reclamation plant in Los Angeles County and the Sacramento regional wastewater treatment plant in Sacramento. The D.C. Tillman water reclamation plant (WRP) had a flow rate of 59 MGD and a solar PV system of 0.4 MW installed on the roof top of the operational building. 0.4 MW was the biggest solar PV system viable for the plant since the rooftop area prevented the adoption of a bigger system. D.C. Tillman WRP did not recover biogas from anaerobic digestion on-site. The sewage sludge generated at D.C. Tillman was instead used to power the Hyperion wastewater treatment plant (Los Angeles), the biggest wastewater treatment plant in California. This lack of on-site biogas generation at D.C. Tillman is likely to have influenced the decision of investing in the rooftop solar PV system.

Sacramento was the only plant that installed a system bigger than 1MW. Their 4.2 MW system occupies 85,000 $m^2$, which is 25% of the total plant footprint, producing only 8% of the plant's energy needs. Land requirement is therefore a significant barrier for the installation of solar PV in large wastewater treatment plants, which are often located close to large urban areas (Figure 4). Sacramento wastewater treatment plant represented an interesting exception because, despite the location in proximity of the city, the wastewater treatment plant is surrounded by a buffer area used to separate the plant from the city. This area, bought in the 1970's, provided the ideal space to install a large solar array (RegionalSan, 2016).

With solar PV contributing so little energy, large plants rely predominately on biogas to cover their energy needs. In the 14 plants above 50 MGD, biogas covered at least 70% of the plant energy needs. Large wastewater treatment plants have to overcome the significant initial and ongoing costs associated with biogas usage by securing long-term economic agreements with third parties. For example, Point Loma wastewater treatment plant in San Diego sells the excess biogas to BioFuel Energy to power the University of San Diego and the City of San Diego South Bay Water Reclamation Plant (SoCalGas, 2018). East Bay Municipal Utility District (EBMUD) in Oakland accepts external feedstock to enhance biogas generation and sells the electricity to the port of Oakland (Hanson, 2014). The biggest wastewater treatment plant in California, Hyperion in Los Angeles, has entered a power purchase agreement with a local energy company, Constellation. Constellation manages the cogeneration facility that runs on the biogas produced by the wastewater treatment plant and sells the energy back to the plant at a fixed price (Constellation, 2014). The Joint Water Pollution Control Plant (JWPCP) in Carson is part of a network of seven wastewater treatment plants and it is the final receiver of the sewage sludge produced by the other plants. The sewage sludge from the seven plants produced more biogas energy than the JWPCP needs, and the surplus electricity is sold to the energy grid (LACSD, 2015).

## 4.5. Limitation and future directions

This work did not conduct an economic analysis of the energy costs and incentives available to wastewater treatment plants in California. Even if the lack of a cost analysis does not affect the significance of these results, it limits the understanding of how and when the incentive schemes function as drivers for the adoption of renewable energy sources in the wastewater sector. Economic incentives play a key role in the development of renewable energy generation, as identified by Foley (2010), who performed an economic analysis of the adoption of solar PV in wastewater treatment plants in Singapore. Therefore, future work will need to identify the economic feasibility of solar PV and hybrid solar PV-biogas systems under different incentive scheme scenarios.

This work did not consider the effect of other renewable energy sources beside biogas on solar PV adoption (e.g. wind and hydro). However, this effect could not be investigated due to the scarcity of data on the adoption of such technologies in California. For example, the data mining process could only identify two wastewater treatment plants adopting wind power and only one using hydro, making it impossible to identify any statistically significant correlation. The lack of wastewater treatment plants installing these technologies could however mean that solar PV is preferred to hydro and wind in California. These two technologies are heavily influenced by the topography of the area where the plants are located, making solar PV a more flexible solution.

# 5.Conclusions

This work assessed the current status of solar PV adoption across different Californian wastewater treatment plants and considered three key factors affecting its integration in the sector. 41 of the 105 plants studied installed a solar PV system for on-site energy generation. Solar PV adoption critically depended on the size of the wastewater treatment plants, since 40 of the 41 plants with solar PV had a flow rate below 59 MDG. Above 59 MGD solar PV systems were not installed unless specific circumstances occurred. The size of the wastewater treatment plants influenced the adoption of solar PV systems, but it did not influence the size of the solar system installed. 1 MW was the most adopted solar installation regardless of the size of the plant.

In wastewater treatment plants with a flow rate above 5 MGD, the presence of anaerobic digestion for energy purposes seemed to positively influence the installation of solar PV in hybrid energy configurations. Coupling biogas and solar PV increased the flexibility of the energy management strategies of the plants, contributing to offset the energy demand of the plants. For plants in this flow range, biogas contributed the most to the overall energy demand, ranging between 25% and 65%, while solar provided between 8% and 30% of the energy needs. In wastewater treatment plants with a flow rate below 5 MGD, the absence of energy generation from biogas drove the adoption of solar PV. In these plants, solar PV often represented the only source of renewable energy, producing between 30% and 100% of the energy demand of these plants. Solar PV installations were mostly found in wastewater treatment plants in rural settings where space for solar installation was not a limitation.

Californian wastewater treatment plants represented an ideal case study because of the high data availability, however, similar trends can be expected in regions with similar conditions and solar radiation.

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