Technical Appendix

GHG Emissions Reduced

	Measure	GHG Reductions 2025-2030 ($mtCO_2e$)	GHG Reductions 2025-2050 ($mtCO_2e$)
Annual	Measure 1 (Landfill Solar)	5,866.17	3,217.19
	Measure 2 (Cattle-Voltaics)	20,129.01	11,039.39
	Measure 3 (WWTP Solar)	2,093.29	1,126.32
	Measure 4 (WWTP RNG)	414.88	477.70
Cumulative	Measure 1 (Landfill Solar)	23,289.27	72,931.54
	Measure 2 (Cattle-Voltaics)	79,914.16	250,255.29
	Measure 3 (WWTP Solar)	10,362.30	26,531.65
	Measure 4 (WWTP RNG)	2,489.27	12,420.20
	Total	116,055.00	362,138.68

See *GHG Emissions Reductions Calculations Spreadsheet - City of Cheyenne* for complete analysis)

Measures 1-3: Solar Documentation

GHG Emissions Reduction Estimate Methodology and GHG Emissions Reduced

Annual GHG reductions calculations for the solar projects, or Measures 1-3, between 2025-2030 and 2025-2050 follows the following formula:

Annual GHG Reductions = renewable energy GHG emissions – BAU GHG emissions

OR:

*Annual GHG Reductions = (added electricity generation from RE in MWh) * (RE Emission Rates) - (reduced electricity generation from BAU grid in MWh) * (Annual emissions rate in BAU scenario in kg CO_2e per MWh)*

ASSUMING:

1 MWh of electricity generated from renewable energy = 1 MWh of electricity generated from BAU grid

AND:

Renewable energy emissions rates = zero (0)

THEN:

*Annual GHG Reductions ($kgCO_2e$) = (Reduced electricity generation from BAU in grid in MWh) * (Annual emissions rate in BAU scenario in $kgCO_2e$ per MWh)*

To calculate annual emissions in $mtCO_2e$, kg is converted to $mtCO_2e$ at 100kg per mtCO2e.

$$\text{Annual GHG Reduction}(mtCO_2e) = \frac{(\text{reduced electricity generation from BAU grid in MWh}) * (\text{Annual emissions rate in BAU scenario in } kgCO_2e \text{ per MWh})}{100}$$

We used NREL's Long-run Marginal Emission Rates for Electricity (LRMER) to estimate the annual emissions rate in a BAU scenario, explained in detail in the models/tools section. Based on 2018 NREL blog on the lifetime of PV panels, the median degradation rate is assumed to be 0.5% per year.[xliii] The annual emissions in a BAU scenario are calculated using the MWh produced each year (as described in the Measure-Specific Activity Data section), accounting for a 0.5% degradation rate, multiplied by the LRMER annual emissions rate for the specific time period. Annual emissions calculations are in columns

D and H starting at row 16 of tabs "Measure 1 Landfill", "Measure 2 Cattle Voltaics", and "Measure 3 WWTP Solar".

To calculate the cumulative GHG emissions per measure, the annual emissions for each year within the time period are added together. Measures 1 and 2 annual GHG emissions are accounted for beginning in 2027, the first full year the projects are projected to be in service. Measure 3 annual GHG emissions are accounted for beginning in 2026, the first full year the project is projected to be in service. Cumulative emissions calculations for each time period for each measure are in cells D13 and D14 of tabs Measure 1 Landfill", "Measure 2 Cattle Voltaics", and "Measure 3 WWTP Solar".

See table at beginning of *Technical Appendix* for GHG emissions reduced.

Models/Tools Used

Emission rates per MWh are estimated using NREL's Long Run Marginal Emission Rates for Electricity (LRMER) tool, which uses Cambium 2023 data.[xliv] The LRMER tool was used because it offers regionally-specific emissions rates for electricity sector and performs better than an average emission rates tool such as eGRID or a Short Run Marginal Emissions Rate tool such as AVERT, as described in minute 34 of this NREL Learning webinar.[xlv] The annual Levelized LRMER for the *West Connect North region* is used since that is the region Cheyenne is located in.

GHG Reduction Estimate Assumptions

The assumptions used for the LRMER tool are (reflected in tabs 'LRMER 2030 Data 2026 Start', 'LRMER 2030 Data 2027 Start', 'LRMER 2050 Data 2026 Start', and 'LRMER 2050 Data 2027' Start):

1. CO_2e to account for methane, nitrous oxide, and carbon dioxide
2. A combined emissions stage to account for combustion and precombustion processes (fuel extraction, processing and transport)
3. Start year of 2027 for Measures 1 (landfill) and 2 (cattle-voltaics) since the solar panels will be placed in service at the end of 2026 and start year of 2026 for Measure 3 (WWTP solar) since the solar panels will be placed in service at the end of 2025
4. Evaluation period for 2025-2030 emissions: 4 years for Measures 1 and 2 which are being placed in service at the end of 2026 and 5 years for Measure 3 which is being placed in service at the end of 2025
5. Evaluation period for 2025-2050: 24 years for Measures 1 and 2 which are being placed in service at the end of 2026 and 25 years for Measure 3 which is being placed in service at the end of 2025
6. Discount rate is 3% - the default rate in LRMER.
7. The mid-case scenario is used since Wyoming has an all-of-the-above energy strategy. The state plans to continue to leverage fossil fuel resources and renewable resources, indicating the grid will not decarbonize sooner than expected.
8. 100-year *IPCC Fifth Assessment Report* data is used for the global warming potential, as requested in the NOFO
9. Location is end use, as is most electrical consumption.

Reference Case Scenario

The reference case for the solar GHG reductions is the emissions from the equivalent electricity produced on the grid as would be produced with solar. LRMER accounts for electric sector state, regional and federal policies, electricity generation technology costs and performance, fuel prices, and electricity demand growth (Cambium 2023 Scenario Descriptions and Documentations, page 8).[xlvi] This includes the impact of the Inflation Reduction Act, CHIPS and Science Act, and Bipartisan Infrastructure Law on the electricity market.

Implementation Assumptions & Measure-Specific Activity Data

Measures 1-3: Solar Sizing and Production

The projected capacity (in MWdc) for each ground-mounted solar project is based on the assumption of approximately 5.3 acres per 1 MW and the available acreage determined by the City.

This assumption of acres per MW is based on evaluating completed project data from US EPA's Repowering America's Lands Tracker (data through October 2023) with the following methodology:[xlvii]

1. Filtering only for *solar* projects *greater than 1 MW* in capacity;
2. Removing any projects that have *incomplete data* for either capacity or project acreage;
3. Calculating *each* project's acreage per MW; and
4. Calculating the *average of all* acreage per MW project data.

This results in an average of 5.3 acres per MW.

To determine viable project acreage, we worked with the site and facility owners, identified viable direct areas for potential solar deployment, and then assumed only 70% of that acreage to be technically viable land available to account for other limiting factors including existing infrastructure, setbacks from roads and wind turbines, and variations in topography. The solar capacity factor is identified using the NREL's PVWatts Calculator to estimate annual electricity production (kWh and MWh) to arrive at the amount of electricity consumed that this project is estimated to offset from the grid. [xlviii]

As described in the *solar GHG reduction estimate method section*, the amount of MWh generated by solar is assumed to be equivalent to the MWh avoided from a BAU grid and the emission rates from solar are assumed to be zero.

	Total Acres	Viable Acres (70% of total)	Estimated Capacity (MW)	Capacity Factor	Estimated kWh
Measure 1: Landfill Solar	102 (figure 1)	71.4	13.47	17.2%	20,298,076.98
Measure 2: Cattle-Voltaics	350 (figure1)	245	46.23	17.2%	69,650,264.15
Measure 3: WWTP Solar	32 (figures 2 & 3)	22.05	4.16	17.6%	6,414,303.40
Total Solar	484	338.45	63.86	N/A	96,362,644.53

The degradation rate of the solar panels is assumed to be 0.5% per year based on 2018 NREL blog on the lifetime of solar panels.[xliii] This means that the estimated production (kWh) will decrease by 0.5% each year, compared to the prior year, reflected in the 'Annual GHG reductions year-over-year calculations' table on tabs "Measure 1 Landfill", "Measure 2 Cattle Voltaics", and "Measure 3 WWTP Solar".

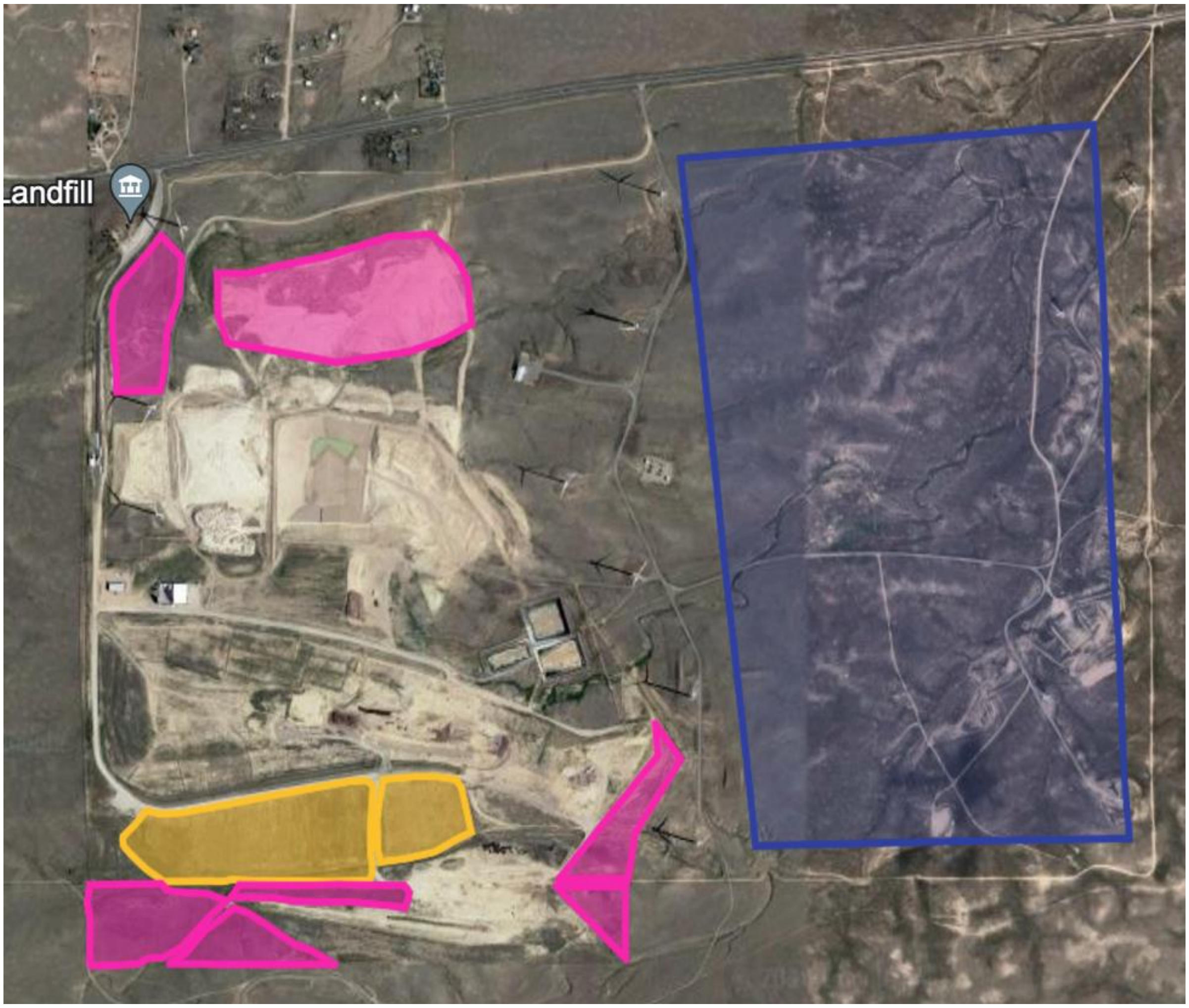

Figure 1: Available acreage for measures 1 and 2. In pink, the landfill buffer areas (70 acres). In yellow, the closed landfill (32 acres). In purple, the cattle-voltaics (350 acres). Image: Google Earth.

Figures 2 (left) and 3 (right): Available acreage for measure 3. Figure 2 shows the available acres at Dry Creek WWTP (18 acres) and figure 3 shows the available acres at Crow Creek WWTP (14 acres). Image: Google Earth.

Battery Sizing and Curtailment Optimization to Support Measures 1-2
As discussed in *Section 1* and the *Budget Narrative, Measures 1 and 2*, the landfill solar and cattle-voltaics would connect to the grid at the same location of the Corriedale Wind Farm to streamline interconnection and increase emissions reductions. Because these use the same existing interconnection point but have different power production profiles, the City project team worked with BHE to optimize for amount of solar installed (between both Measures 1 and 2) with a reasonable curtailment rate (no more than 20%).

Curtailment rate optimization is based partly on Black Hills Energy's (BHE) analysis as well as this study that shows even with curtailment at 20%-40% electricity prices can be cost effective and reach grid parity.[xlix] We assume the conservative end (20%) of that range as the target below in an internal analysis conducted by BHE.

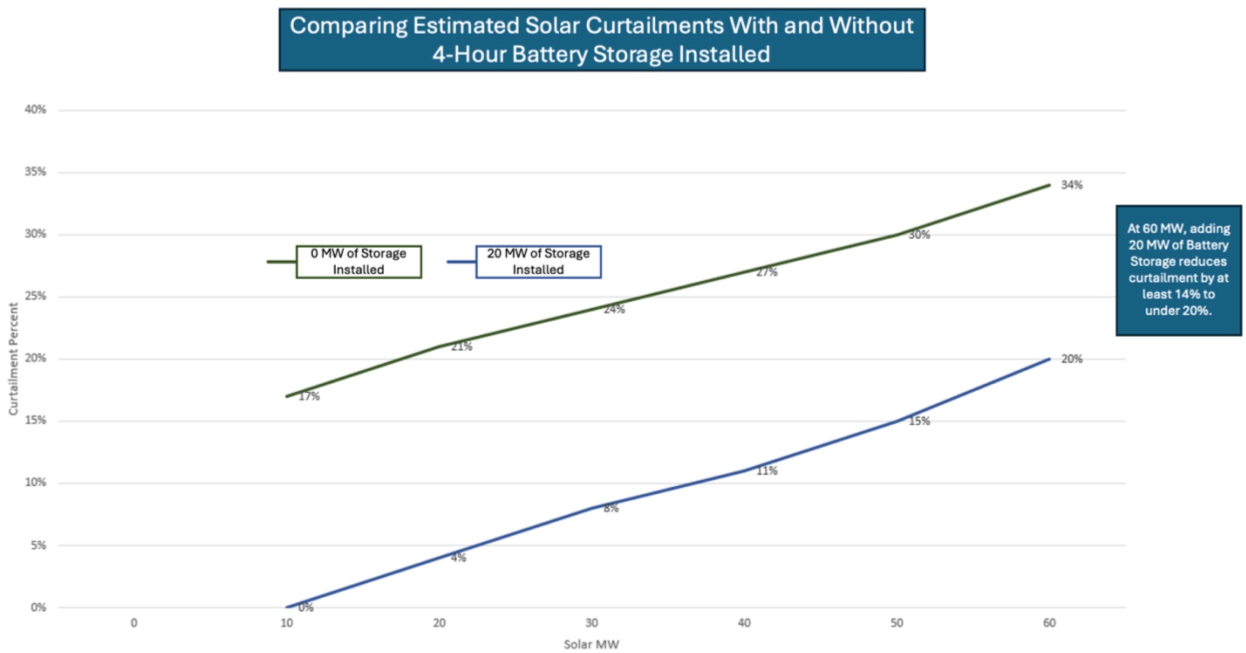

Chart courtesy of Black Hills Energy, March 2024.

Battery-Related Emissions Reductions
How utility-scale battery storage is used can meaningfully impact the benefits, including potential emissions reductions. Prospective use cases include reducing resource curtailment to maximize renewable energy operations (as discussed above) mitigating peak demand charges, reducing the need for inefficient and high emissions peaker plants, and providing resilience and reliability enhancements in the event of grid outages or severe weather events. Beyond resource curtailment and enhanced grid reliability, the City and BHE have not yet determined the optimal other use cases for this battery storage. This will be the topic of community engagement, developer negotiations, and ongoing bilateral discussions. Accordingly, this application only assumes emissions reductions from Measures 1-4. We consider the battery *complementary to enabling the scale of solar proposed* (and corresponding emissions reductions), and do not assume any emissions reductions directly from the battery. This is likely very conservative, but we did not want to misrepresent the impact given multiple potential use cases and ongoing planning.

Measure 4: WWTP RNG Infrastructure Technical Documentation

GHG Reduction Estimate Method and GHG Emissions Reduced

Producing and ultimately using renewable natural gas (RNG) offsets consumption of fossil-based natural gas. When fossil-based natural gas is burned, it produces CO_2. Because biogas would otherwise be flared and produce CO_2, RNG production reuses this otherwise wasted biogas to displace fossil-based natural gas consumption in other facilities.

RNG production is, however, limited by the kilograms (kg) of solids available. The quantity of solids available is predominantly a function of how much is produced by Cheyenne's population. As a result, expected population growth/decline is also accounted for in the year-over-year annual GHG reductions. The kg of solids assumes a 0.92% population increase, based on the population increase in Cheyenne between 2010-2020, resulting in a higher production of RNG each year and therefore a larger annual GHG reduction each year.[xxii]

The GHG reductions calculations for installing RNG infrastructure to produce RNG at the Dry Creek facility are based on the 2022 Argonne National Laboratory (ANL) study, Opportunities for Recovering Resources from Municipal Wastewater, and the following assumptions and approach applies:[l]

- This study calculated the GHG reductions potential of municipal wastewater treatment facilities across the U.S. by comparing BAU scenarios to various anaerobic digestion with energy recovery scenarios. The analysis included Dry Creek WWTP in Cheyenne.
- The BAU scenario assumes GHG emissions from flaring the biogas produced.
- The proposed RNG infrastructure project most closely resembles the *AD2 scenario* from the ANL study, described later in this section. This scenario assumes no flaring and that GHG emissions from fossil natural gas are offset by the RNG produced.
- Note: The GHG emissions estimates are based on kg of solids processed at the facility. According to BOPU, by updating the kg of solids processed at the facility to the actual kg of solids processed at the facility, the same calculations can be used to find the actual GHG emissions for the BAU and the RNG infrastructure (AD2) scenarios. These calculations can be found on tabs "WWTP BAU Data" and "WWTP AD2 Data" in rows 907-933.
- Once the GHG emissions for the BAU and RNG infrastructure scenarios are calculated (tabs 'WWTP BAU Data rows 907-933' and 'WWTP AD2 Data' rows 907-903), the annual GHG reductions are calculated by taking the difference of the two scenarios, as shown in tab 'Measure 4 WWTP RNG' J17-J43. In other words, the year over year emissions savings are the difference between implementing Measure 4 (RNG offset plus zero flaring) and the BAU scenario (only biogas flaring)
- The cumulative GHG reductions are calculated by adding the annual GHG reductions for the time period (tab 'Measure 4 WWTP RNG' K48-K49). Because the project will be placed in service halfway through 2025, GHG reductions begin halfway through 2025. The annual GHG emissions under the AD2 scenario in 2025 are divided by 2 to reflect this (tab 'Measure 4 WWTP RNG' F18).

See table at beginning of *Technical Appendix* for GHG emissions reduced.

Models/Tools Used

The GHG reductions are based on the 2022 Argonne National Laboratory (ANL) study: Opportunities for Recovering Resources from Municipal Wastewater.[l] This study created a database of 15,008 municipal wastewater treatment facilities in the US using the 2008 and 2012 Clean Watersheds Needs Survey (CWNS) database and the EPA Integrated Compliance Information System National Pollutant Discharge Elimination System (ICIS NPDES). Additional data on current WWTP operations was synthesized from the US DOE combined Heat and Power (CHP) installation database, the WEF's biogas database, and municipality websites where updated information was available. The database factors in the current technology of each municipal wastewater facility.

The authors analyzed various pathways to compare to a BAU scenario, including anaerobic digestion with combined heat and power to produce RNG for distribution (scenario called AD2). The AD2 pathway (Figure 5) beneficially uses the products of anaerobic digestion to generate heat and power for on-site use and to generate RNG. The biogas undergoes two cleanup processes to remove H2S and siloxanes, then CO2 and water to produce pipeline quality RNG. The biosolids are also used as fertilizer to further reduce emissions. GHG emissions are calculated based on emissions associated with compressing, transporting, distributing, and combusting RNG, fuel displacement credits (for burning an equivalent amount of RNG as fossil natural gas in a BAU scenario), fertilizer displacement credits, and avoided facility BAU GHG emissions.

<u>GHG Reduction Estimate Assumptions</u>
The assumptions used in this GHG reduction calculation follow the assumptions of the ANL report. See tab 'WWTP Assumptions Data' for the full list of assumptions. Notably, ANL assumes that the carbon dioxide emissions from biogas and its combustion are generally considered to be carbon neutral as they are associated with organic matter composed of carbon originally taken up from the atmosphere during plant growth. From another perspective, emissions from anaerobically digested biogas can be considered to offset the emissions which would have occurred had the solids and sludge been managed by other means (2022 ANL report, page 5).

<u>Reference Case Scenario (BAU)</u>
The Dry Creek WWTP uses anaerobic digestion and flares the biogas product (Figure 4). According to the Cheyenne WWTP plant manager at BOPU, Matthew Buelow, the plant processes 3,220 kg of solids a day and 1,175,300 kg of solids a year. This BAU scenario is reflected in the ANL methodology and data but requires a modification on the kg of solids.

In the BAU scenario, the ANL data accurately says that Dry Creek uses anaerobic digestion with flaring (Tab 'WWTP BAU Data' N907). The fossil fuel emissions calculated in a BAU scenario accounted for the emissions associated with flaring. However, the solids reflected in this analysis are not accurate. ANL reports that Dry Creek processes 1,778,392.18 kg of solids a year, when in fact, they process 1,175,300 kg of solids a year. The original ANL data was adjusted to reflect the actual kg per year, since the GHG emissions calculations are based on kg of solids. The ANL formulas then calculated the mmBtu of CO2e for the BAU scenario (Tab 'WWTP BAU Data' row Z) with the accurate kg of solids.

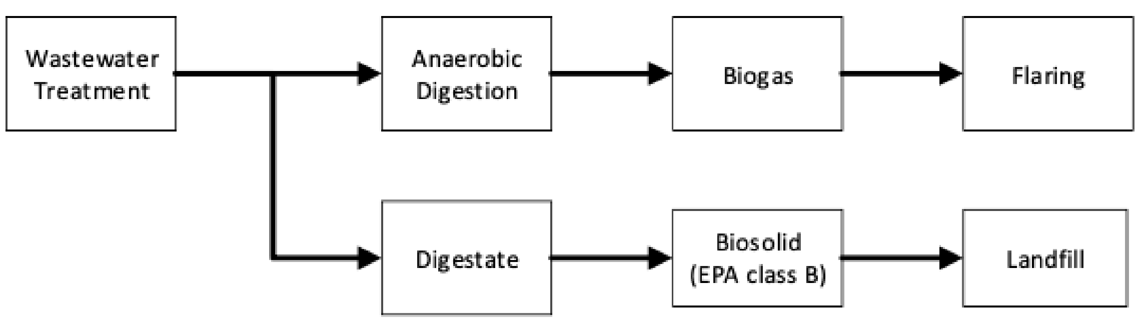

Figure 4: Anaerobic digestion with flaring process. BAU at Dry Creek. Image: Argonne National Laboratory

Implementation Assumptions and Measure-Specific Activity Data

BOPU seeks to retrofit the Dry Creek facility to add RNG conversion infrastructure. As shown in Figure 5, they plan to use biogas from the first clean up as heat and electricity for the facility. They will use the product of the second clean up, RNG, for market consumption as compressed natural gas through BHE's distribution system.

The ANL AD2 scenario is used to estimate the GHG emissions reductions from the RNG infrastructure retrofit since the scenario's pathway matches BOPU's intended pathway, with some modifications. ANL's AD2 scenario accounted for GHG reductions from fertilizer displacement credits. Since BOPU is not planning to utilize the solids for soil application, the GHG reduction estimates from this part of the pathway were removed (see tab 'WWTP AD2 Data' columns W, X, and Y). In addition, the kg of solids was modified in the AD2 scenario as it was in the BAU scenario, to reflect the actual kg of solids processed.

With these modifications, the formulas by ANL were used to calculate the GHG reductions from the RNG infrastructure scenario (Tab WWTP AD2 Data, AD). These calculations are based on kg of solids processed at the facility.

The GHG reductions are calculated assuming the amount of biogas extracted from the kg of solids will remain constant throughout the lifecycle, which is conservative. The City is planning to install a new heat exchanger in November 2024 which will make the digesters more efficient, so they can extract more biogas from the solids. This will increase the amount of RNG produced at the facility, but it cannot be accounted for quantitatively yet.

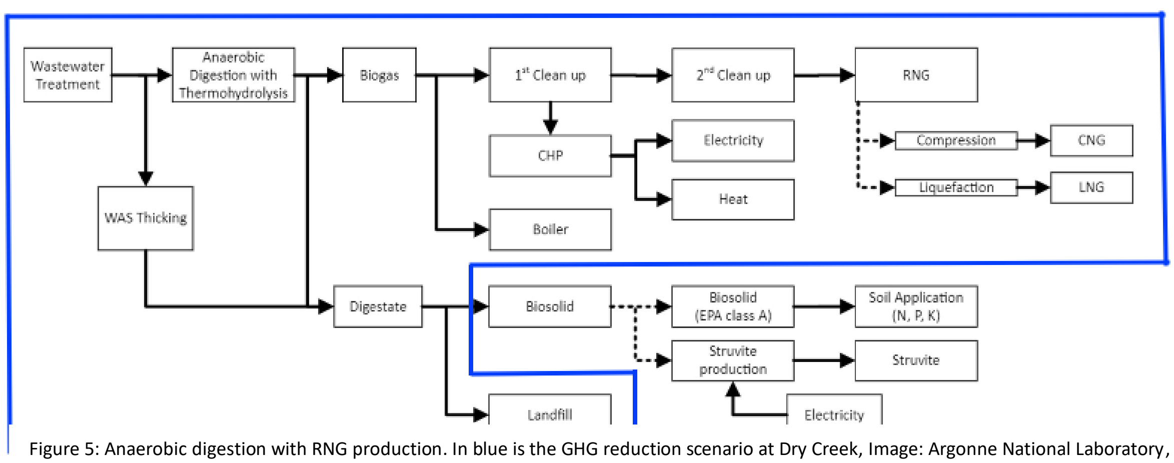

Figure 5: Anaerobic digestion with RNG production. In blue is the GHG reduction scenario at Dry Creek, Image: Argonne National Laboratory, adjusted to show intended process at Dry Creek

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