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Anaerobic Digestion Analysis Model: User's Manual

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1. Introduction

The Anaerobic Digestion Analysis Model (**ADAM**) has been developed to assist investigators in performing preliminary economic analyses of anaerobic digestion processes. The model, which runs under Microsoft Excel™, is capable of estimating the economic performance of several different waste digestion process configurations that are defined by the user through a series of option selections. The model can be used to predict required feedstock tipping fees, product selling prices, utility rates, and raw material unit costs.

The model is intended to be used as a tool to perform preliminary economic estimates that could be used to carry out simple screening analyses. The model's current parameters are based on engineering judgements and are not reflective of any existing process; therefore, they should be carefully evaluated and modified if necessary to reflect the process under consideration. The accuracy and level of uncertainty of the estimated capital investment and operating costs are dependent on the accuracy and level of uncertainty of the model's input parameters. The underlying methodology is capable of producing results accurate to within ±30% of actual costs.

This model builds off the MSWAD model developed by R. Legrand and T.M. Todd, described in the technical report "Systems Analysis of Municipal Solid Waste Biogasification" (1). **ADAM** was developed with funds provided by the United States Environmental Protection Agency.

2. Model Overview

ADAM was developed on Microsoft Excel™ Version 4.0, and thus requires Excel™ releases 4.0 or later to be used. The model consists of five worksheets: an input/output (I/O) worksheet (*IO.XLS*), a material and energy balance worksheet (*MATBAL.XLS*), an equipment worksheet (*EQUIP.XLS*), a cashflow analysis worksheet (*CASHFLOW.XLS*), and a worksheet containing the macro programming modules (*MCROS.XLA*). All five worksheets must be open to run the model, but only the I/O worksheet (*IO.XLS*) is necessary to enter all the required parameters and to read the results

calculated by the model. The MCROS.XLA worksheet is automatically opened, and is hidden from view as an add-in macro sheet.

Descriptions of the processes that can be simulated are given below. These descriptions do not include a discussion of the underlying technology, as it is assumed the user possesses this knowledge. Rather, these are general descriptions of the model's organization. The process flow diagrams, which are useful for following this discussion, can be found in Appendix A. Parameters used in the material and energy balance worksheet can be found in Appendix B.

2.1. Preprocessing Section

ADAM allows the user to select up to three feeds of digestible material. For the first feed stream, municipal solid waste (MSW), the user has several different options for separation. The second feed stream is a liquid and the third is a solid; both are assumed to be ready to enter the digester without further preparation. The primary difference between the second and third feed streams is that the second is transported through pipes with pumps while the third is transported on belt conveyors. Three options are available for separation of the MSW: mechanical sorting, manual sorting, and green loading (i.e., minimal sorting).

Option 1. Mechanical Sorting

For mechanical sorting of MSW, material is collected in a receiving lot **(Stream 1000)** and bulldozed onto the first conveyor at the specified flow rate **(Stream 1010)**. On this conveyor, the only manual sorter in the process removes glass, placing it onto CNV-1013 **(Stream 1013)** for transport to the Glass Storage Bin **(BIN-1013)**. Stored glass is periodically removed from the glass storage bin by a glass recycler. The remaining MSW is shredded by a hammer crusher **(MLH-1010)**. Most of the ferric material in the MSW is then removed by a conveyor magnet **(MGN-1020)**. The size of the remaining MSW **(Stream 1040)** is further reduced by a hammer mill **(MLH-1040)**.

The reduced material **(Stream 1050)** is transported to a course disk screen **(SCR-1050)**. The screen removes the larger material **(Stream 1060)**, which is mixed with excess filtrate from the digester section **(Stream 3110)** and/or additional process water **(Stream 1070)**. This wet material enters a trommel **(TRO-1090)**. Most of the plastics will not fall though the trommel; they are removed and conveyed **(Stream**

1100) to a plastics holding bin. The material that falls through the trommel **(Stream 1120)** is pumped to the feed blending tank **(TNK-2200)**.

The removed plastics can be recycled, landfilled, or incinerated with the solid residue. If the plastics are recycled, the amount a recycler will pay for them can be entered in the model. If the plastics are landfilled, the landfilling fee is included as an expense. Finally, the plastics can be incinerated if the solid residue from the digester is being incinerated.

The material that passes through the course disk screen **(Stream 1130)** is conveyed to a can disk screen **(SCR-1130)**. The fraction that is removed by the can disk screen **(Stream 1140)** passes under a conveyor magnet **(MGN-1140)**, where most of the remaining ferric material is removed. This ferric material is then conveyed **(Stream 1150)** to the same iron holding tank that contains the previously removed iron **(TNK-1150)**. From there, the iron is trucked to a recycler. The material that is not removed by the magnet passes over an eddy-current separating hub **(ECS-1170)** while switching conveyors. There, aluminum is removed **(Stream 1180)** and conveyed to a holding bin **(BIN-1180)** before being taken to a recycler. The MSW that passes over the eddy-current separator **(Stream 1190)** is conveyed to the mixing tank **(TNK-2200)** before entering the digester.

The material that passes through the can disk screen **(SCR-1130)** is filtered by a fine disk screen **(SCR-1300)**. Material removed by the fine disk screen **(Stream 1310)** enters an air stoner **(AST-1310)** to remove light nondigestable materials; e.g., tiny scraps of plastic. The MSW that is not removed by the air stoner **(Stream 1350)** is conveyed to the mixing tank **(TNK-2200)**. The material that passes through the fine disk screen **(Stream 1400)** enters an air knife **(AKN-1400)**, which is a cyclone designed to remove heavy nondigestable material; e.g., stones and glass shards. The heavy nondigestible material **(Stream 1430)** is stored in a bin **(BIN-1430)** with the light nondigestible material before it is trucked to a landfill. The digestible material passes through the air knife **(Stream 1450)** and is conveyed to the mixing tank **(TNK-2200)** before entering the digester.

Option 2. Manual Sorting

Under the second option for separating MSW, manual sorting, laborers remove the recyclable material from the MSW stream before it is crushed. The MSW is received in a lot designated for that purpose **(Stream 1000)** and is bulldozed onto a conveyor to enter the sorting area **(Stream 6000)**. The first material to be sorted by hand is glass, which is removed **(Stream 6020)** and stored **(BIN-6020)** for recycling. Similarly, iron and steel **(Stream 6040)** and aluminum **(Stream 6060)** are removed and stored for recycling. Finally, plastic is removed **(Stream 6080)** and sent to the plastic holding bin **(BIN-6080)**. In the plastic processing option, the user may choose to recycle, landfill, or incinerate the plastic.

After the materials have been sorted, the size of the MSW is reduced by a hammer crusher **(MLH-6090)** and a hammer mill **(MLH-6091)** in series. The material is then conveyed **(Stream 6100)** to a mixing tank **(TNK-6100)** where it is mixed with excess filtrate from the digestion section **(Stream 3110)** and/or process water **(Stream 6110)** to increase its moisture content. The moist material then enters a wet trommel **(TRO-6120)**. Most of the material passes through the trommel and is pumped **(Stream 6140)** to the feed blending tank **(TNK-2200)** before entering the digester. The rejects are too large to pass through the trommel screens and are conveyed **(Stream 6030)** back to the front of the process to be mixed with the entering, unsorted MSW.

Option 3. Green Loading

The third MSW sorting alternative is green loading. This option is chosen for material that is sorted before it is transported to the facility or for homogeneous material that does not require sorting, such as organic waste pick-ups.

The material is received **(Stream 1000)** and is bulldozed onto a conveyor to be transported to sorting **(Stream 7000)**. One sorter is present to remove all of the rejects **(Stream 7010)**, which are stored before being transported to a landfill. The size of the remaining MSW is reduced by a hammer crusher **(MLH-7020)** and a hammer mill **(MLH-7021)** in series. The reduced MSW stream is conveyed **(Stream 7030)** to the feed blending tank **(TNK-2200)** before entering the digester.

2.2. Digestion

The shredded MSW in the feed blending tank **(TNK-2200)** is mixed with the other wastes, if present, the recycle from the digester **(Stream 3090)**, if any, and dilution water **(Stream 2200)**, if necessary.

After blending **(TNK-2200)**, the feed is heated and pumped into the digester **(Stream 3030)**. Two digester options are available: RefCoM (Refuse Converted to Methane) low-solids digestion and NRELHS (National Renewable Energy Laboratory High Solids) high-solids digestion. The RefCoM digester is a continuously stirred tank reactor (CSTR). The NRELHS digester is a slightly-mixed, horizontal-flow reactor fed with a 30% solids slurry. The residence time of the feed is normally 14-20 days and the conversion of volatile solids to biogas is 70-75%.

The feed is preheated to the digester temperature before entering the digester. The RefCoM system uses a condensing steam heat exchanger to heat the feed **(HX-3000)**. The NRELHS system uses a agitated tank with a condensing steam jacket **(TNK-3000)** to heat the feed. The digester temperature should remain above ambient because the reaction is exothermic and the digesters are designed to be well-insulated.

The digestion products are a medium Btu biogas **(Stream 3050)** and a solid residue **(Stream 3060)**. The medium Btu biogas is approximately 55% methane, 43% carbon dioxide, and 2% hydrogen sulfide on a dry molar basis and is saturated with water. The solid residue consists of the undigested solids, cell-mass, and water.

The user has the option of dewatering the solid residue after it leaves the digester with a belt filter press. If the residue is not dewatered, it is conveyed to the solid residue processing section **(Stream 3070)**. If the residue is dewatered, some of the filtrate is recycled **(Stream 3090)** to dilute the feed to the digester. The filtrate is also pumped to the wet trommel in the MSW preprocessing section if the mechanical or manual sorting option is chosen **(Stream 3100)**. The dewatered solids are conveyed to the solids residue processing section **(Stream 3070)**.

2.3. Biogas Processing

Four options are available for processing the biogas after it leaves the digester: sale of the medium Btu gas, production of synthetic natural gas (SNG) from the biogas, production of methanol from the biogas, and production of electricity from the biogas. In all four options, the hydrogen sulfide and water are removed from the biogas **(Stream 4020)**. A flare is present to be used if needed **(FLR-4030)**.

In the first option, removal of hydrogen sulfide and water produces a clean biogas that is stored and sold as medium Btu gas.

In the second option, the clean biogas is circulated through a membrane-separation process to produce a 95 mole% methane gas **(Stream 4220)**. A fraction of the dilute methane gas removed by the membrane is recirculated to recover some of the remaining methane and the rest is flared. The 95% methane gas is sold as synthetic natural gas.

In the third option, the clean biogas is circulated through a membrane-separation process that concentrates the methane to 75 mole%. A 75%/25% CH_4/CO_2 ratio is the ideal feedstock for methanol production. The feedstock gas **(Stream 4320)** is steam-reformed to produce synthesis gas that is 33 mole% CO and 67 mole% H. Catalytic reactions convert the synthesis gas to methanol.

In the fourth option, the clean biogas is incinerated to produce electricity. The user has a choice of generators: internal combustion cogeneration, or gas turbine combined cycle. The internal combustion cogeneration generator has a 33% efficiency. The gas turbine combined cycle generator has a 50% efficiency, but is significantly more expensive.

2.4. Solid Residue Processing

The user can choose one of three options for processing the solid residue from the digester: landfilling, incineration, and composting. The landfilling option entails dumping the residue into a truck and sending it to a landfill **(Stream 5100)**. This stream is not dewatered after the digestion section, so the moisture content may be high.

In the incineration option, the residue is dewatered in a screw press (**SCR-5200**), and the filtrate is disposed in the municipal sewer system. The dewatered residue is mixed with the plastics removed in preprocessing if the plastics incineration option is chosen. The solids are then dried in a fluidized-bed dryer (**DYF-5240**) by the hot gases from the incinerator and combusted in an incinerator with an attached boiler. There are two boiler options: producing only enough steam to heat the feed to the digester or producing the maximum amount of steam possible. For the second option, some of the steam is used to heat the feed to the digester and the excess drives a turbine to produce electricity. After the gases from the incinerator pass through the dryer, they are cleaned in a Venturi scrubber. The solid waste from the incinerator is mixed with the liquid waste from the Venturi scrubber and is landfilled.

For the composting option, the residue is dewatered in a screw press and delumped to break up the larger pieces. It then passes through a trommel designed to remove the noncompostable materials that have passed through the preprocessing section; e.g., glass shards and metal pieces. The solids are allowed to mature on a composting platform, where an optional windrow may be used to increase the maturation rate and decrease the odor. The mature compost is usually used as a soil additive.

3. Model Use

The model consists of five worksheets: An I/O worksheet (*IO.XLS*), a material and energy balance worksheet (*MATBAL.XLS*), an equipment worksheet (*EQUIP.XLS*), a cashflow analysis worksheet (*CASHFLOW.XLS*), and a worksheet containing the macro programming modules (*MCROS.XLA*). All four worksheets with the XLS extension must be open to run the model, but only the I/O worksheet is needed to enter the necessary parameters and read the results calculated by the model. A series of examples that demonstrate the model are given in Appendix C. Microsoft Excel™ gives the user the option of calculating results automatically or manually at the user's request (Options Calculation menu). However, if the calculation option is not set to automatic, the user could obtain erroneous results by failing to manually recalculate after input has changed since the last manual calculation.

3.1. Input/Output Worksheet

The I/O worksheet (*IO.XLS*) is used to specify the feeds, choose the processing options for each section, specify the digester parameters, and input cost and financing assumptions. The I/O worksheet is the only worksheet that the user must completely understand to be able to use **ADAM**. The worksheet contains nine input sections, a results section, and a summary printout section. The worksheet is designed to be user friendly in that all the input parameters and results are clearly labeled. (*The user will be better able to understand these explanations if the Input/Output worksheet is open and used to follow the discussion.*)

Section 1. Feeds

In the first section, the user specifies the flow rates and compositions of the feeds. The percentages of volatile solids, iron, aluminum, plastics, and glass in the MSW are based on the total flow; therefore, the sum of those percentages cannot be greater than the percent of total solids. If they sum to less than the specified percent of total solids, the unspecified solids are assumed to be ash. EXCEL notes (comments attached to a specific cell that can be viewed through the Formula Notes menu) give common values for each component entered. The cell where feed density is entered also contains a note with a default value.

The second and third feeds also are specified in the feeds section. All three feeds are optional and any can be excluded by entering a flow rate for that feed of zero tons per day. All equipment and energy requirements needed for that feed will be omitted by the model.

Section 2. MSW Preprocessing

In the second section, the user selects the MSW preprocessing option. The desired option is chosen by typing its corresponding letter into cell D7.

Section 3. Digester

The user selects the digester scheme and its parameters in the third section. The user chooses the digester type by entering the corresponding letter into cell F5, and enters its parameters into other cells in column F. Default values can be entered for the NRELHS digester by pressing the "Defaults" button located in cell F3. The user can overwrite any of these defaults by entering the desired value for the parameter.

If the belt filter press option is selected, the maximum fraction of the expressed liquid recycle in the influent is a parameter. That parameter is the maximum mass fraction of the influent stream to the digester **(Stream 3030)** that can be expressed liquid recycled from the belt filter press. If the parameter is set to zero, the influent stream to the digester does not contain any of the belt press filtrate. If the parameter is set to one, all of the dilution water will be supplied by belt press filtrate if the capacity exists. If there is not sufficient capacity, the remainder is supplied by process water. Any fraction between zero and one specifies the maximum mass fraction of the belt press filtrate in the digester influent stream.

The composition of the biogas on a dry basis is specified by entering the molar fractions of methane and hydrogen sulfide. The model calculates the molar fraction of carbon dioxide, the only other component in the dry biogas. The model then calculates the amount of water in the biogas, which is saturated and at atmospheric pressure.

The final parameter entered is the temperature of the feed entering the digester. The digester temperature will be approximately the same as the entering feed because the reactions are exothermic and the digester's insulation is designed to maintain isothermal conditions.

Section 4. Biogas Processing

The biogas processing options are in columns G and H. The user selects an option by entering its corresponding letter into cell H6. If option d, electricity generation, is chosen, the user must also choose between a gas turbine and a combined cycle generator.

Section 5. Solid Residue Processing

In section 5, the user selects the solid residue processing option by entering its corresponding letter into cell J6. The user must choose whether or not a windrow will be used if the composting option is selected.

Section 6. Plastics Processing

For the final processing option, the user selects a plastics processing option by entering its corresponding letter into cell L6. An error message will appear if the incineration option is chosen while the solid residue processing option is not set to either incineration scheme. The error appears because it is assumed that it is uneconomical to purchase an incinerator that would be used solely for plastics incineration.

Section 7. Solvable Costs and Credits

Section 7, Solvable Costs and Credits, is the primary calculation section. This section has four columns: column M is the list of products and services that are sold or purchased, column N is the input column, column O holds default values provided by the model, and column S (with the heading "Solution") is the column where the solution appears.

The user provides input in column N. Three input options are available: the value or cost of the item, "solve," or "lookup." Entering the word "solve" (without quotation marks) in column N specifies the item for which the model will solve for the unit value or cost. "Solve" may be entered for only one item because the model is capable of solving for only a single parameter.

The default value of the item will appear in column O if "lookup" (without quotation marks) is entered in column N. No input by the user is allowed in column O.

Section 8. Financing

The financing section is in columns T and U. The top row in this section reports the total capital investment necessary for the defined facility. If an error (**#NUM!, #VALUE! or #DIV/0!**) is present instead of a value in cell U5, push the "Reset" button in cell M1 above the Solvable Costs and Credits section. That button activates a macro that clears the errors. Below the total capital investment results cell is the interest paid in each year of the plant life. The user should calculate those values using the desired funding method and enter them into the model.

Section 9. Other Factors

The final input section is titled Other Factors. As in Section 7, this section allows for an item's value to be entered or looked up. "Lookup" uses the default values that are in column X.

Solving the Model

The user can solve for the unknown parameter when all choices and data input have been completed. The "**Solve**" button is located in cell M1 above the Solvable Costs and Credits section, and activates the macro that solves the model. When this button is pressed, the model switches worksheets and performs trial-and-error calculations until it satisfies the conditions set by the model. This operation may take several minutes to complete.

Section 10. Results

Other results are reported in the Results section. The landfill life multiplier is the ratio of the MSW volume sent to the landfill not processed by an anaerobic digestion facility to the volume of waste sent to the landfill that has been processed by the defined anaerobic digestion facility to reduce its volume. A warning stating the number of pieces of equipment that are outside of the costing range appears when any piece of equipment is less than one-tenth of the costed size or greater than ten-times the costed size. A solution will still be given when the warning is present, but the error of the capital investment could be greater than ±25%.

Section 11. Summary Printout

This section summarizes the input and results for a one-page printout. It is contained in columns AF-AP and is set as the print area.

3.2. Material and Energy Balance Worksheet

The material and energy balance worksheet (*MATBAL.XLS*) calculates the flow rate and composition of each feed stream. Columns A, B, and C, as well as rows 1-8, are set as titles.

There are several different vertical sections in the worksheet. The first section (Columns D-S) tabulates the component flowrates (units identified in column C) for each process stream. The second section (Columns AH-AZ) tabulates the utility flow rates. The third section (Columns BB-BJ) is a summary section that displays the total stream flow, temperature, density, and volumetric flow rate. The fourth section (Columns CJ-CR) is where the parameters defining the performance of each unit operation are stored and can be modified (Columns BK-BV). The final section (Columns CJ-CO) tabulates the unit costs.

Between each visible row there is a hidden row that can be revealed by using the Format-Row Height-Unhide command. When revealed, each hidden row is shaded and displays the mass fractions of the components in the stream in the row above it.

The parameters used in the calculations that simulate the performance of the unit operations are defined in the parameter section. The calculations, which simulate the unit operations, can be modified by changing the values of the parameters. For example, the fraction of aluminum that is removed by the eddy-current separator can be changed by varying the value in cell BU43. The parameter cells that contain formulas (shaded backgrounds) should not be changed, because changes to them disable the Input/Output worksheet's ability to define the parameter's value.

In the unit costs section, each component and utility is listed in column CK. Nonconventional components (e.g., synthetic natural gas and compost) are at the bottom of the table. Annual consumption or production data for each item are in column CL. The unit price of each item is in

column CN, and is imported from the input worksheet. The unit price of the item being solved for is set to zero.

3.3. Equipment Worksheet

The equipment worksheet displays an equipment list, the sizing and costing calculations, sectional installation factors, and labor cost. The shaded lines display section summaries.

Column A lists the item number as it is designated on the process flow diagrams. Column B lists the number of pieces registered. That number is set to zero if that piece of equipment is not required in the process as defined by the user. If two items are registered, it may mean that two items are required or it may mean that a spare is suggested.

Column C has the heading "Name" and is a short description of the item. Column D lists the capacity or size specifications that were used to cost the equipment. Columns E-H list parameters that are used to calculate the size of each item.

The index ratio is used to update the cost of the equipment in the effective year. This ratio is contained in column N and uses the indices from the journal Chemical Engineering in columns J and M.

Column O lists each item's purchased equipment cost using the sizes listed in column D. The material and pressure factors (columns P and Q) increase or decrease the cost when special materials or extraordinary pressures are necessary. The references for the purchased equipment cost are listed in column R. The total module cost of the reference case process (column S) is calculated by taking the product of the purchased cost, the material factor, the pressure factor, the index ratio, and the number of items.

The next set of columns modifies the cost of each item with changes in its size. The stream reference (column T) specifies a stream that is involved in the determination of the item's size. The reference case factor column lists each item's reference case size, and the case study factor column calculates the size of the item required by the user-defined process. The capacity ratio is the case study factor

divided by the reference case factor. The cost of the case study item (column Z) is the reference case item's cost multiplied by the capacity ratio raised to the capacity exponent (column Y). The cost of equipment for the entire facility is given in cell Z183.

The electrical power requirements are listed in columns AA and AB. The total electrical power requirement by the facility is given in cell AD175.

The remaining columns specify costs that are specific to plant sections rather than individual items. The number of laborers is calculated in columns AC-AG. The costs of shipping, piping, electrical, instrumentation, utilities, and service facilities inside the battery limits; foundations and structural support; insulation; painting; and installation are functions of the equipment cost of each section, and are listed in columns AH-AY. The contingency, engineering and supervision, and utilities and service facilities outside the battery limits are factors of the fixed capital investment. The factors for each section are listed in columns AZ, BA, and BF, respectively, and the factors for the entire facility are a weighted average of the factors for each section.

The labor cost is calculated in columns BI-BP. The total number of supervisors, operators, technicians, and unskilled laborers required for the facility during each shift are listed in cells BL13, BL15, BL17, and BL19, respectively. The salary of each is determined from their hourly wages which are input in the Input/Output worksheet. The annual labor cost is calculated and given in cell BL34.

3.4. Cash Flow Worksheet

The cash flow worksheet (*CASHFLOW.XLS*) is where most of the cash flow calculations are made. It also includes additional financial factors. The factors that can be changed have the same light cell shading as the cells which define the factors.

The cells that can be changed in column D are the investment tax credit, the equipment salvage value, the percent of the fixed capital investment spent in the first and second years, and the percent of the total start-up costs spent in the third year of construction. The other factors are input in the Input/Output worksheet or are calculated elsewhere. All of the factors in cells O3-O16 may be

changed. The factors that can be changed in column AL are yard improvements, land, construction expenses, contractors fees, buildings, start-up costs, annual maintenance and repairs, annual property taxes, annual insurance costs, and the plant location factor.

The working capital section is in columns AS-AW. Each working capital item is listed in column AS. The number of days of inventory for each item can be changed in column AU.

Appendix A — Process Flow Diagrams

The following 16 figures are the process flow diagrams for **ADAM**. Each diagram depicts one section of the facility: MSW preprocessing, digestion, biogas processing, or solid residue processing.

The stream numbers are identified in the diamonds (e.g., 100) and correspond to the stream numbers in the MATBAL.XLS worksheet. The arrowheads (e.g., MSW Feed) contain information as to where the material is flowing to or from. The ovals (e.g., CNV-1010) identify the tag number of each piece of equipment. Solid lines represent streams that are always present in a given processing option and dashed lines represent streams that may or may not be present.

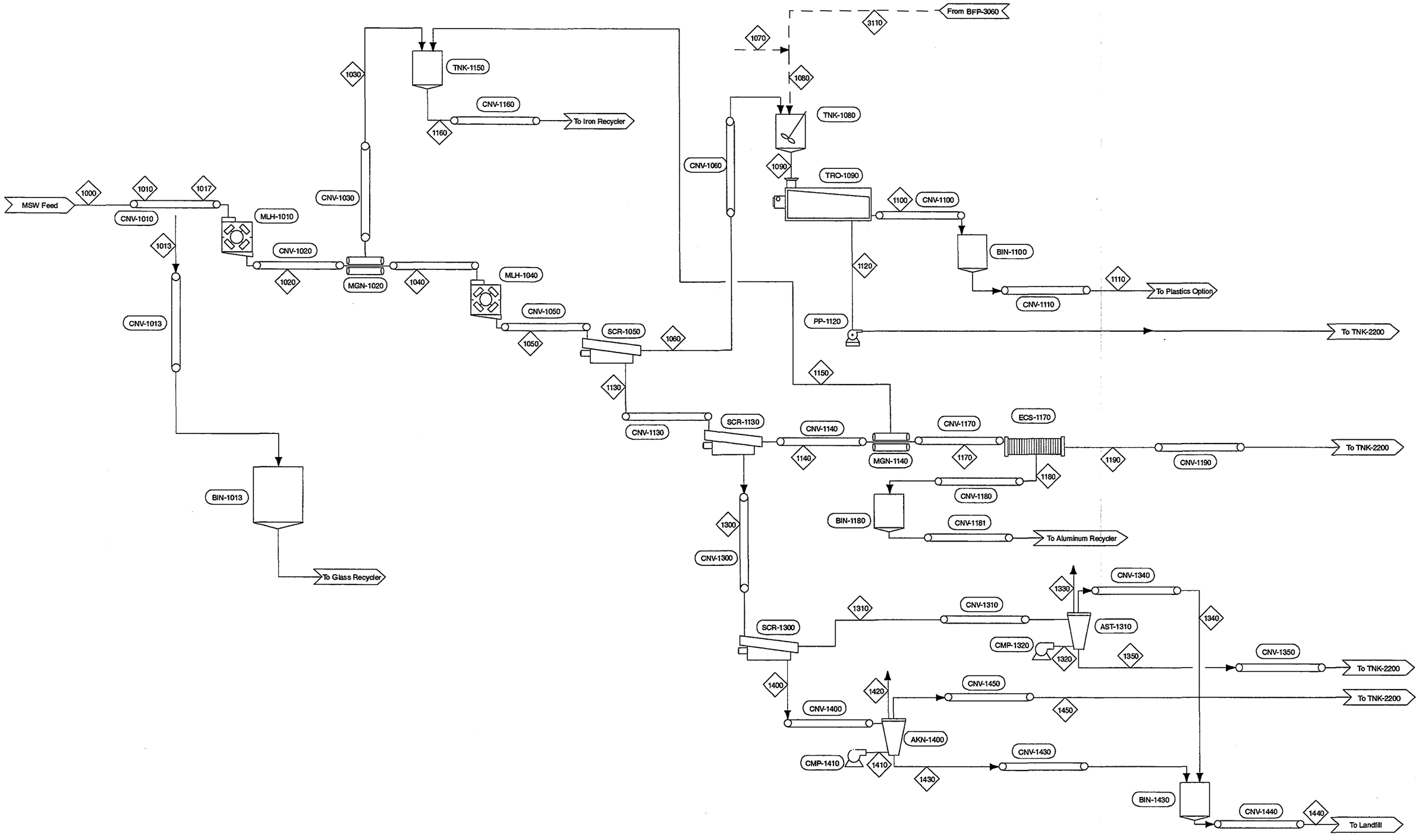

Figure 1. MSW Preprocessing Option A: Mechanical Sorting

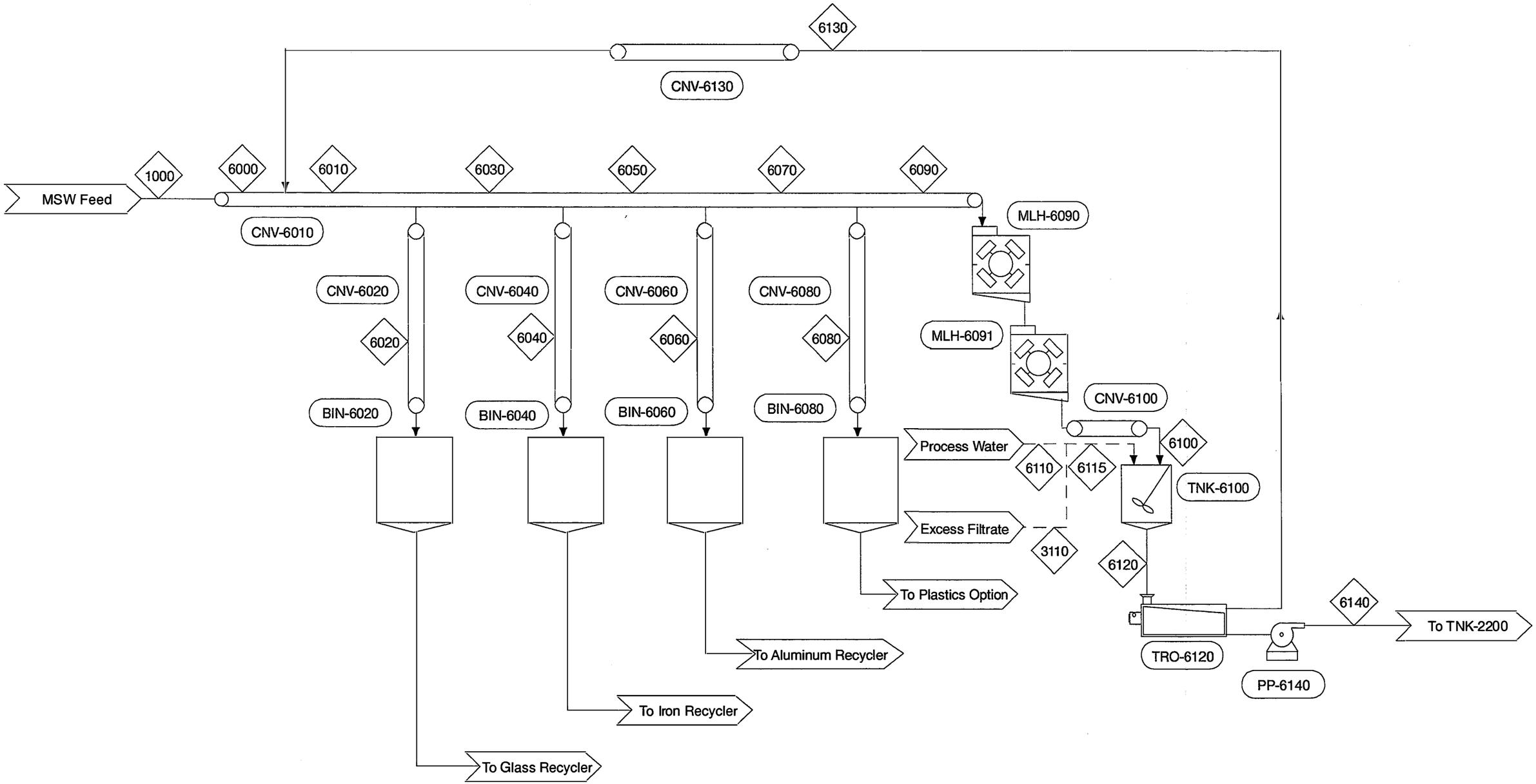

Figure 2. MSW Preprocessing Option B: Manual Sorting

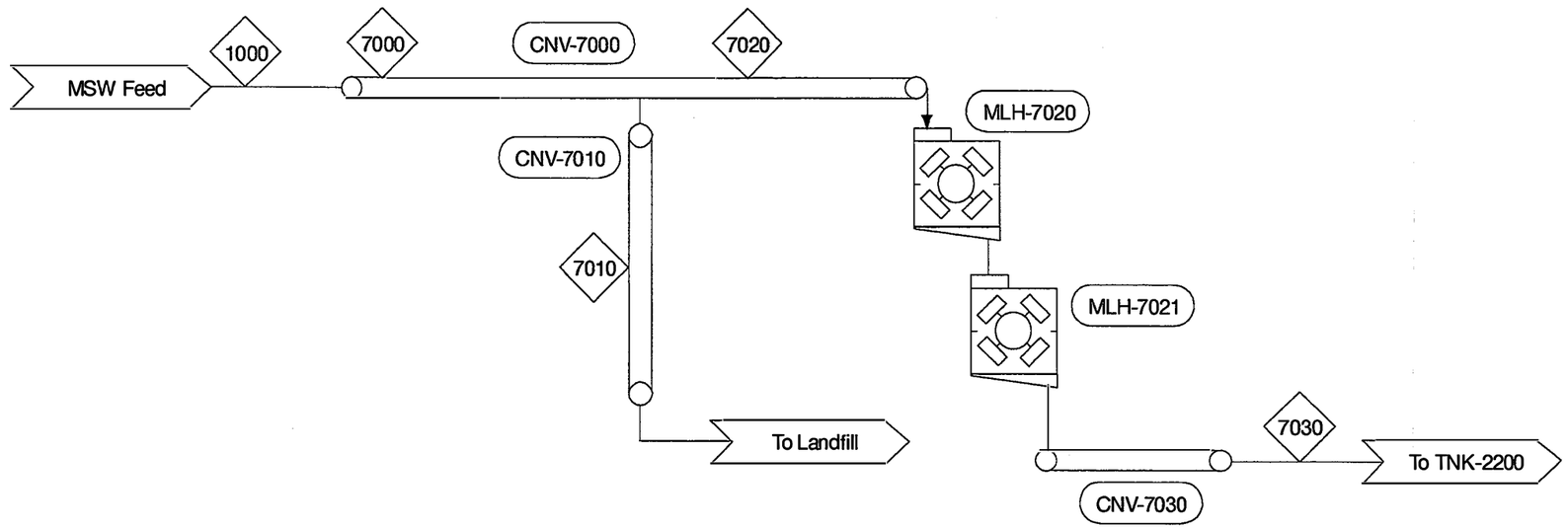

Figure 3. MSW Preprocessing Option C: Green Loading

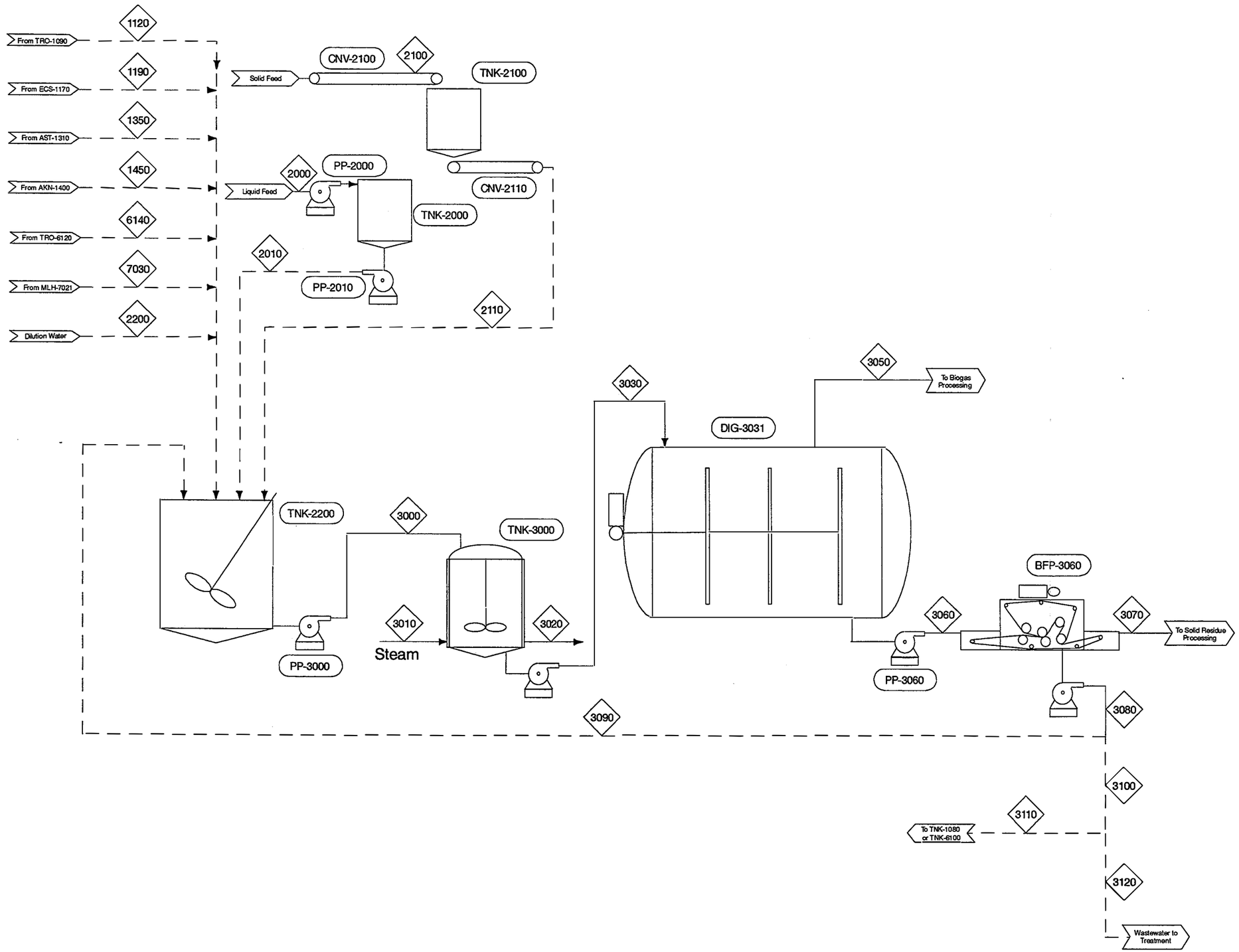

Figure 4. Digestion Scheme Option A: NRELHS Digester with Belt Filter Press

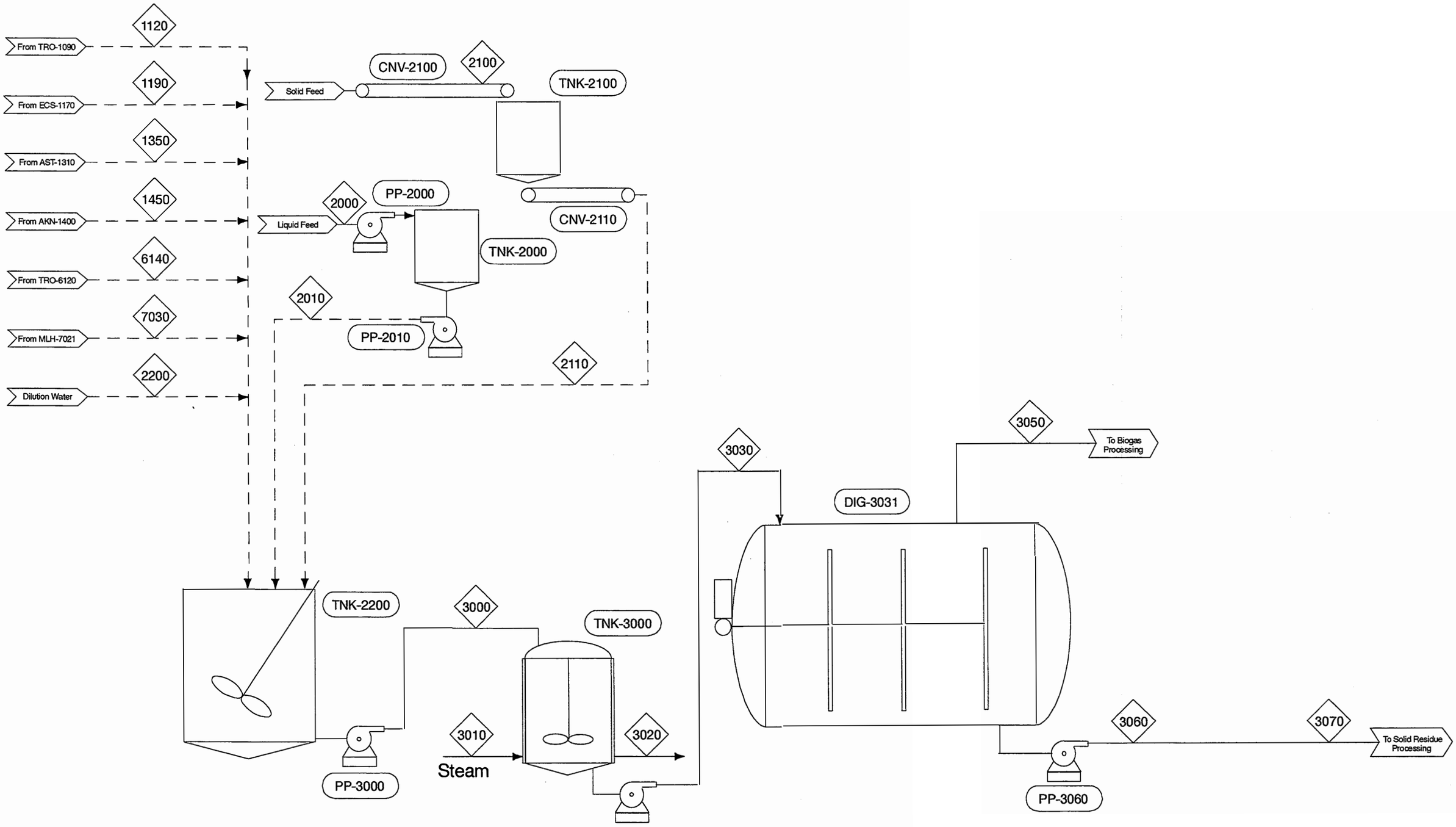

Figure 5. Digestion Scheme Option A: NRELHS Digester without Belt Filter Press

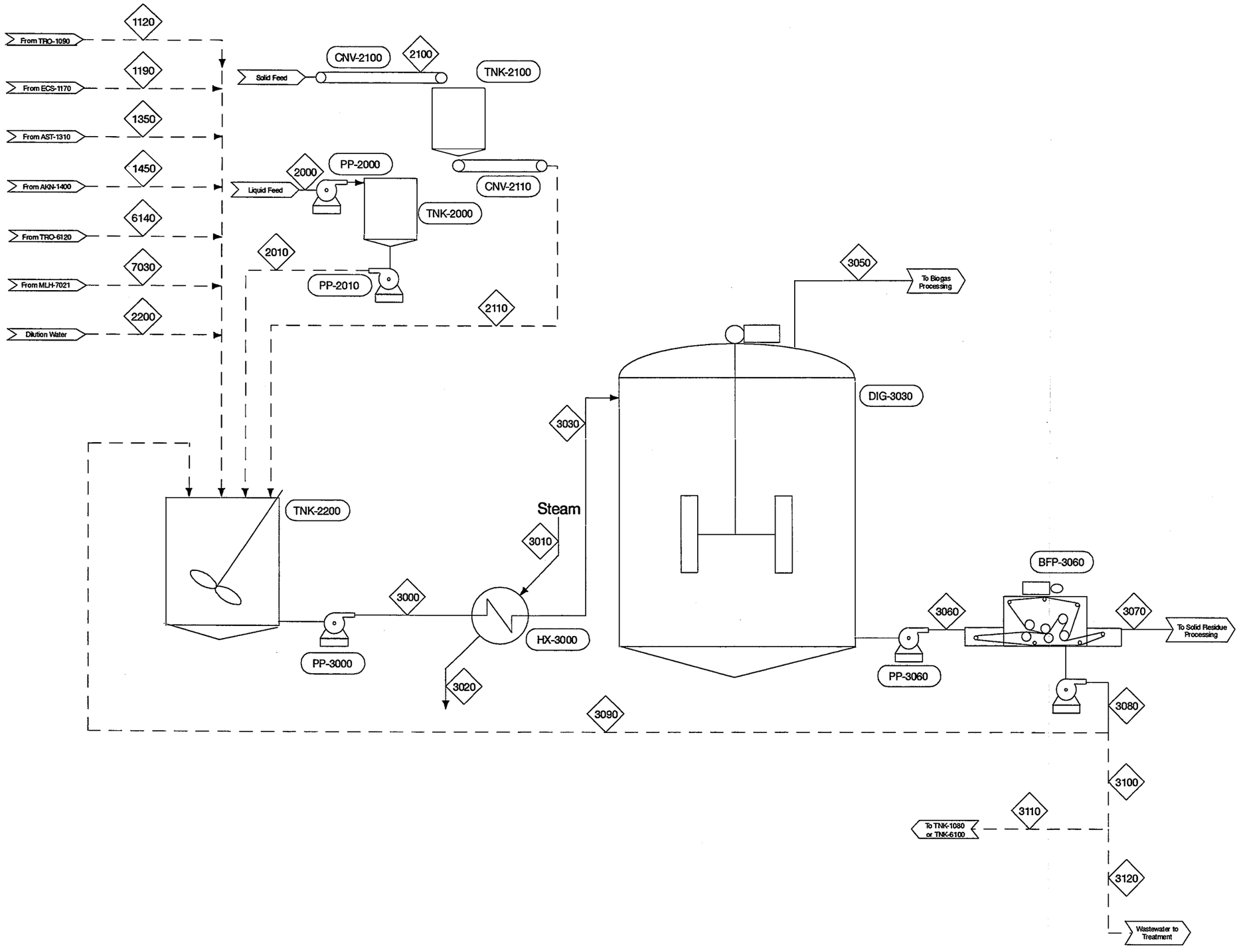

Figure 6. Digestion Scheme Option B: RefCoM Digester with Belt Filter Press

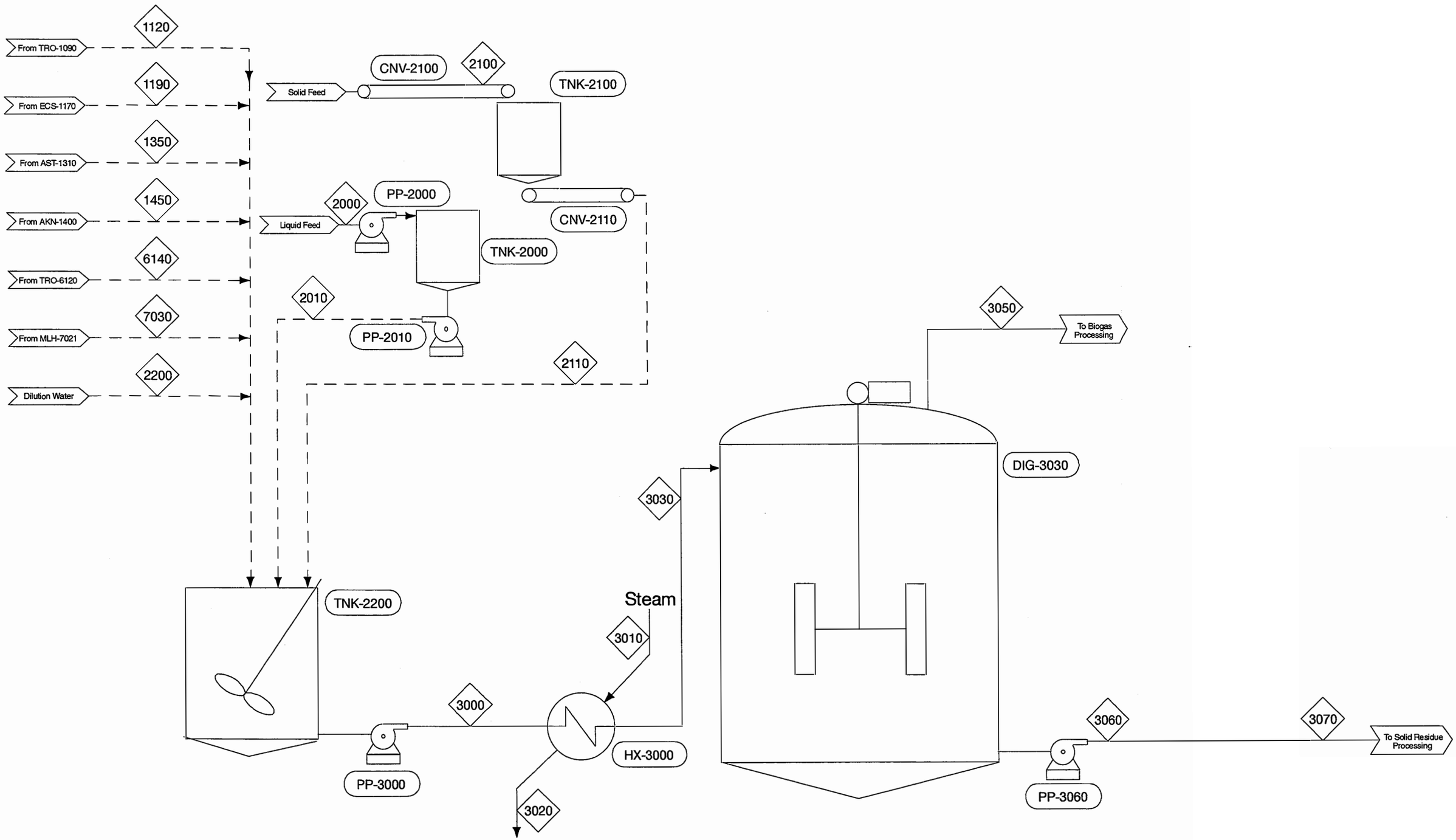

Figure 7. Digestion Scheme Option B: RefCoM Digester without Belt Filter Press

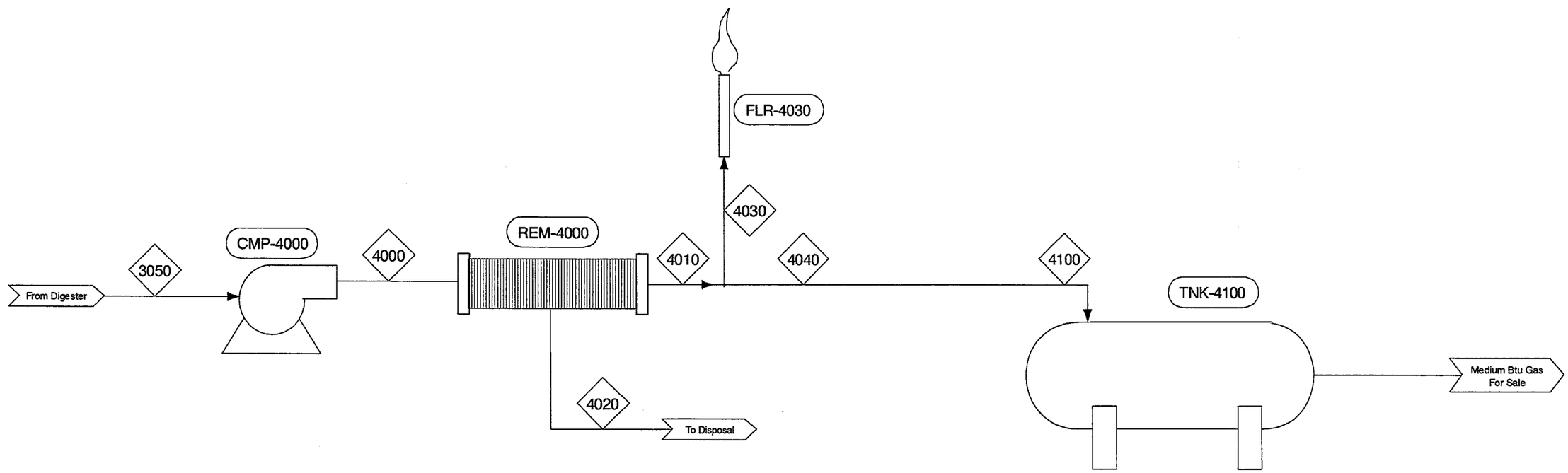

Figure 8. Biogas Processing Option A: Sale of Medium Btu Gas

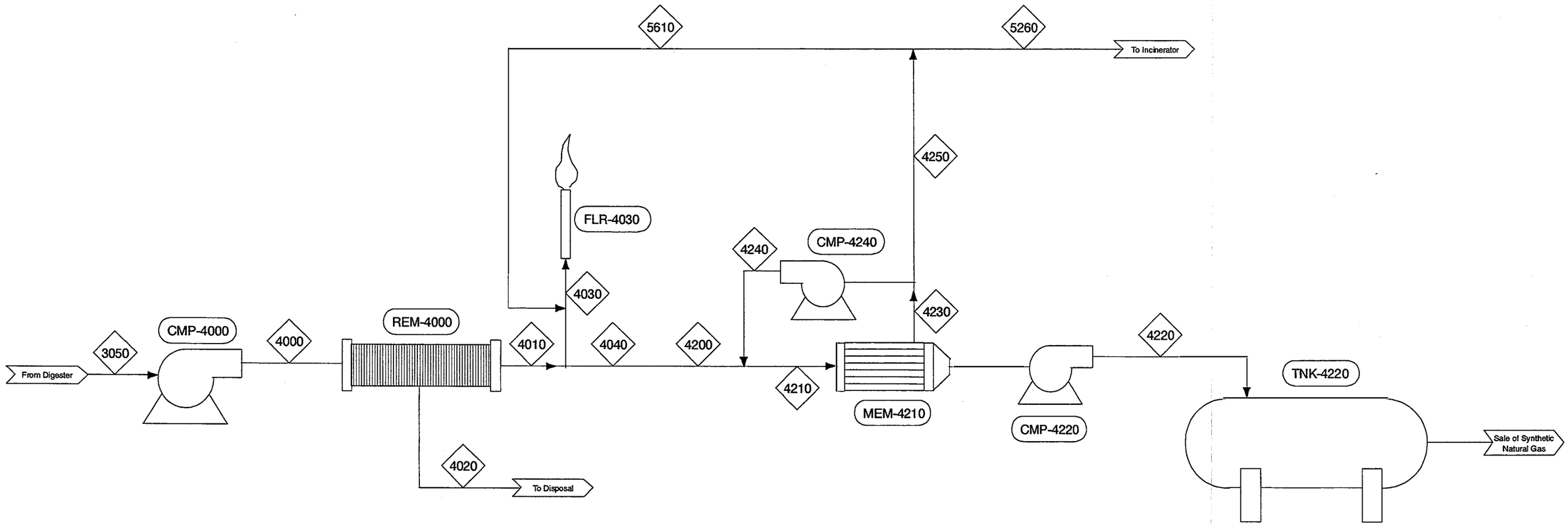

Figure 9. Biogas Processing Option B: Sale of Synthetic Natural Gas

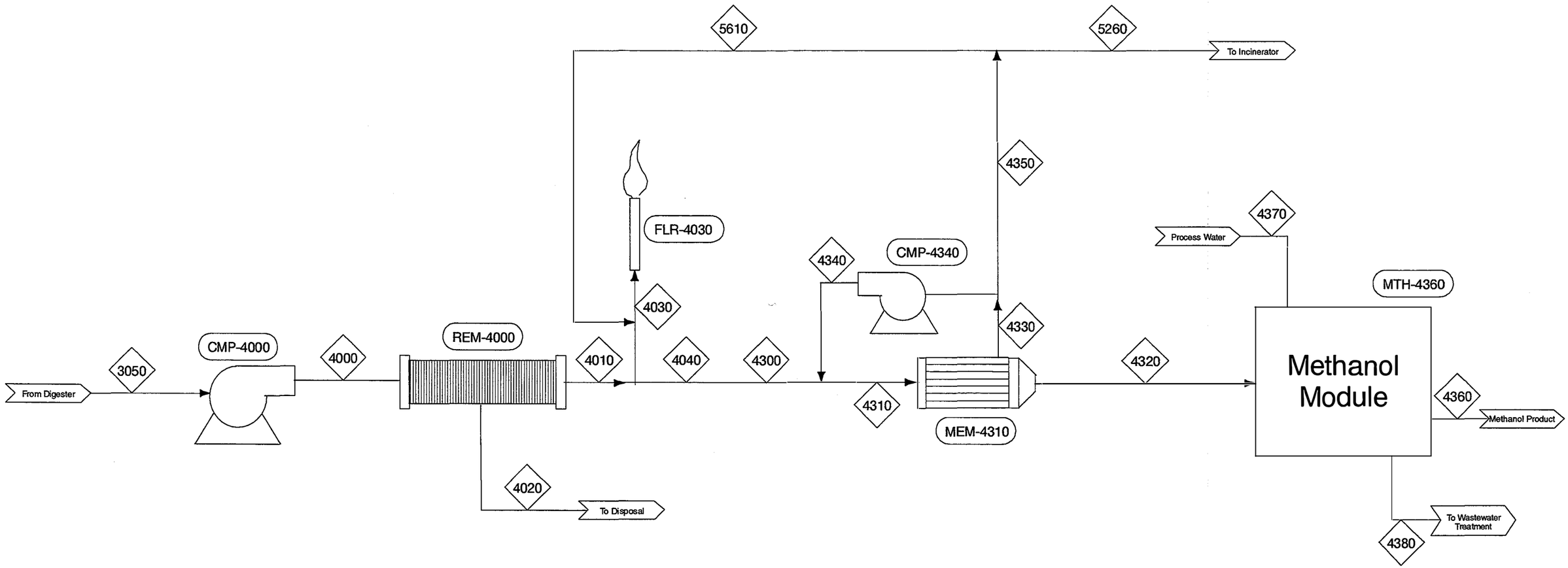

Figure 10. Biogas Processing Option C: Production and Sale of Methanol

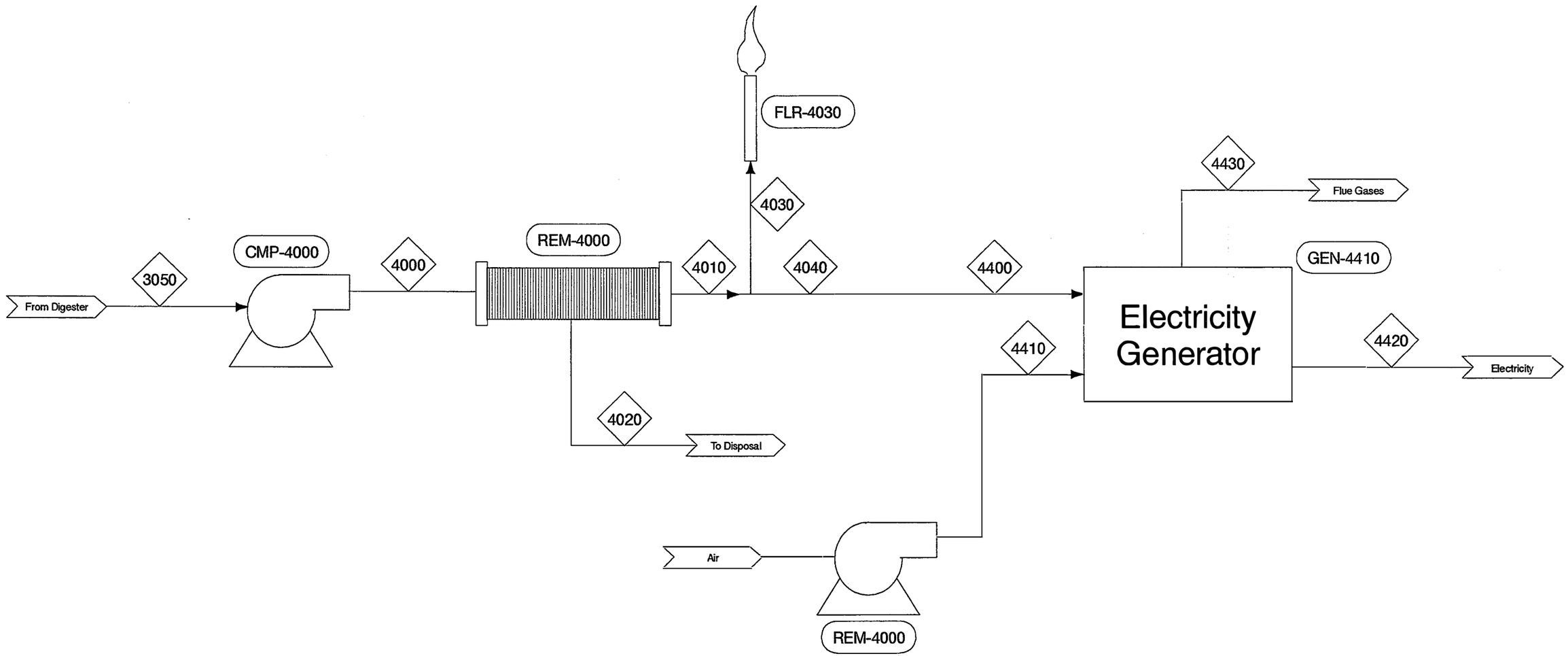

Figure 11. Biogas Processing Option D: Generation and Sale of Electricity

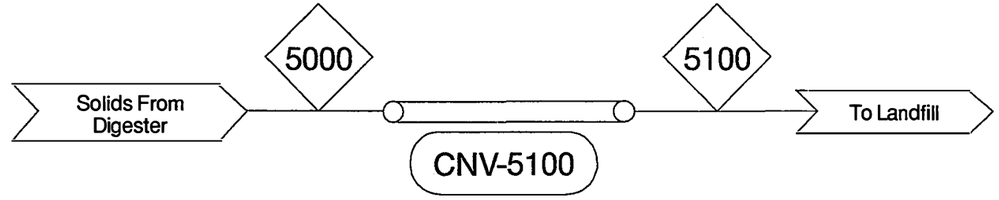

Figure 12. Solid Residue Processing Option A: Landfilling

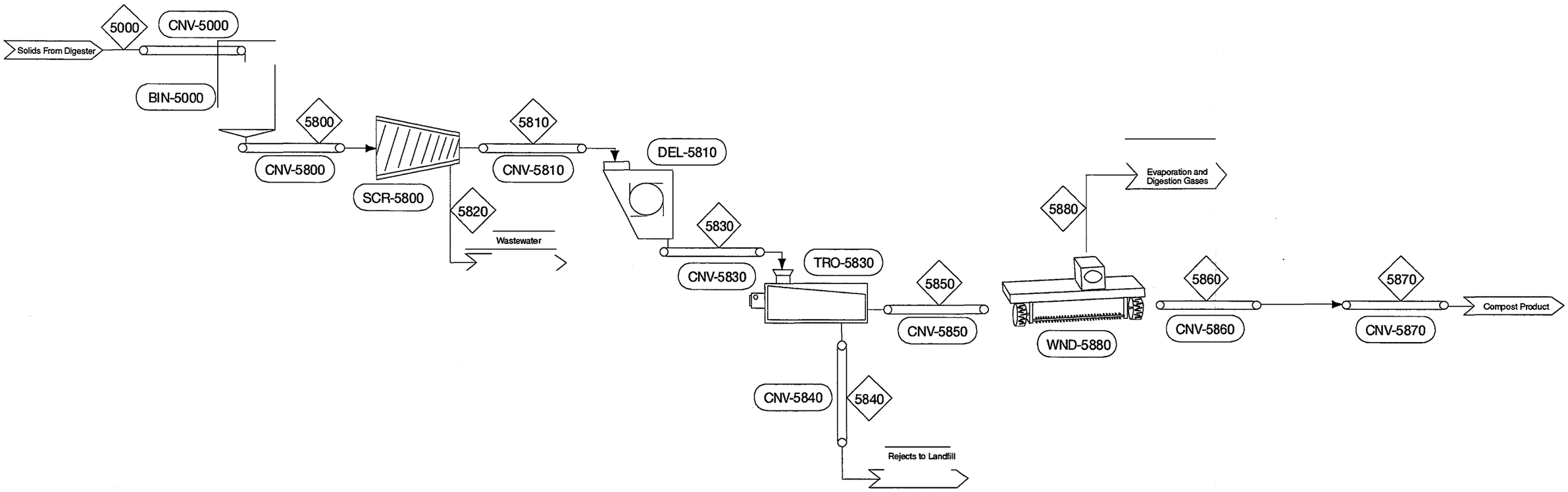

Figure 13. Solid Residue Processing Option B: Composting with Windrow

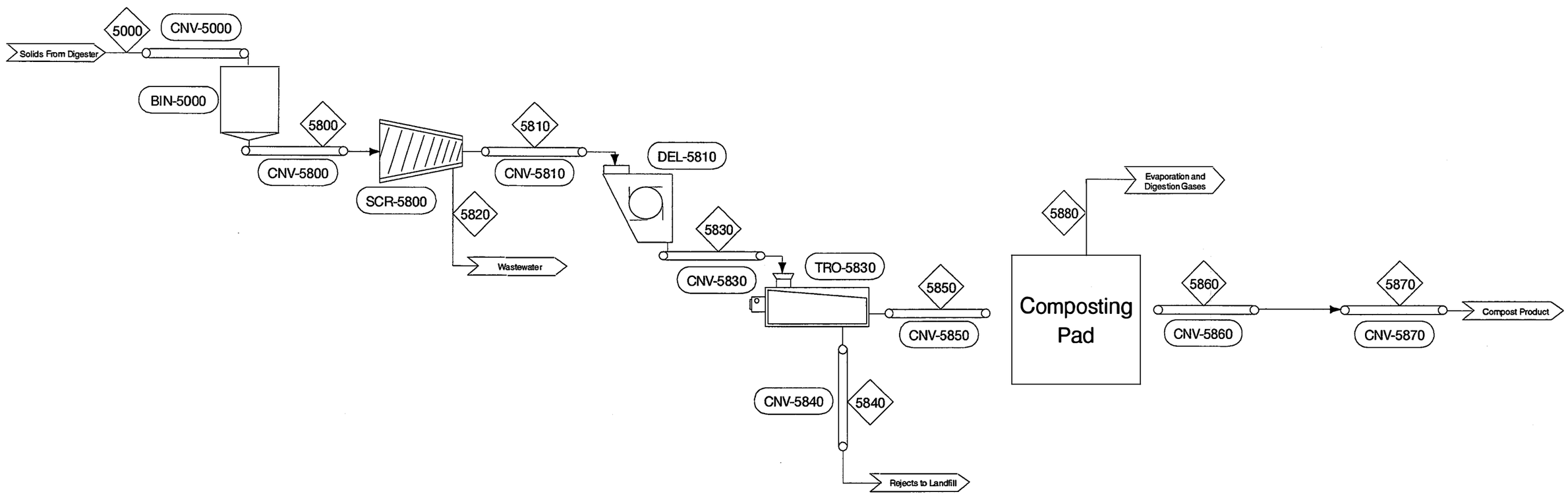

Figure 14. Solid Residue Processing Option B: Composting without Windrow

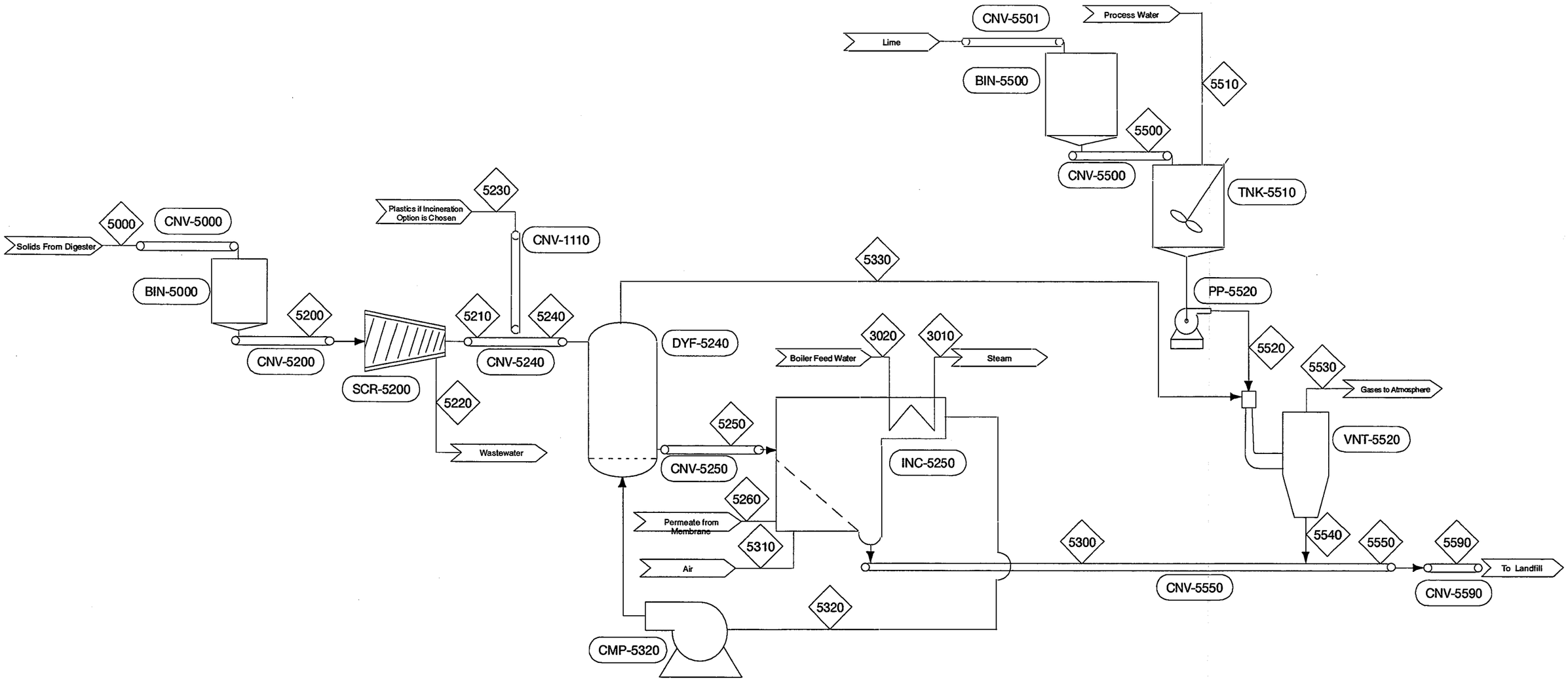

Figure 15. Solid Residue Processing Option C: Incineration

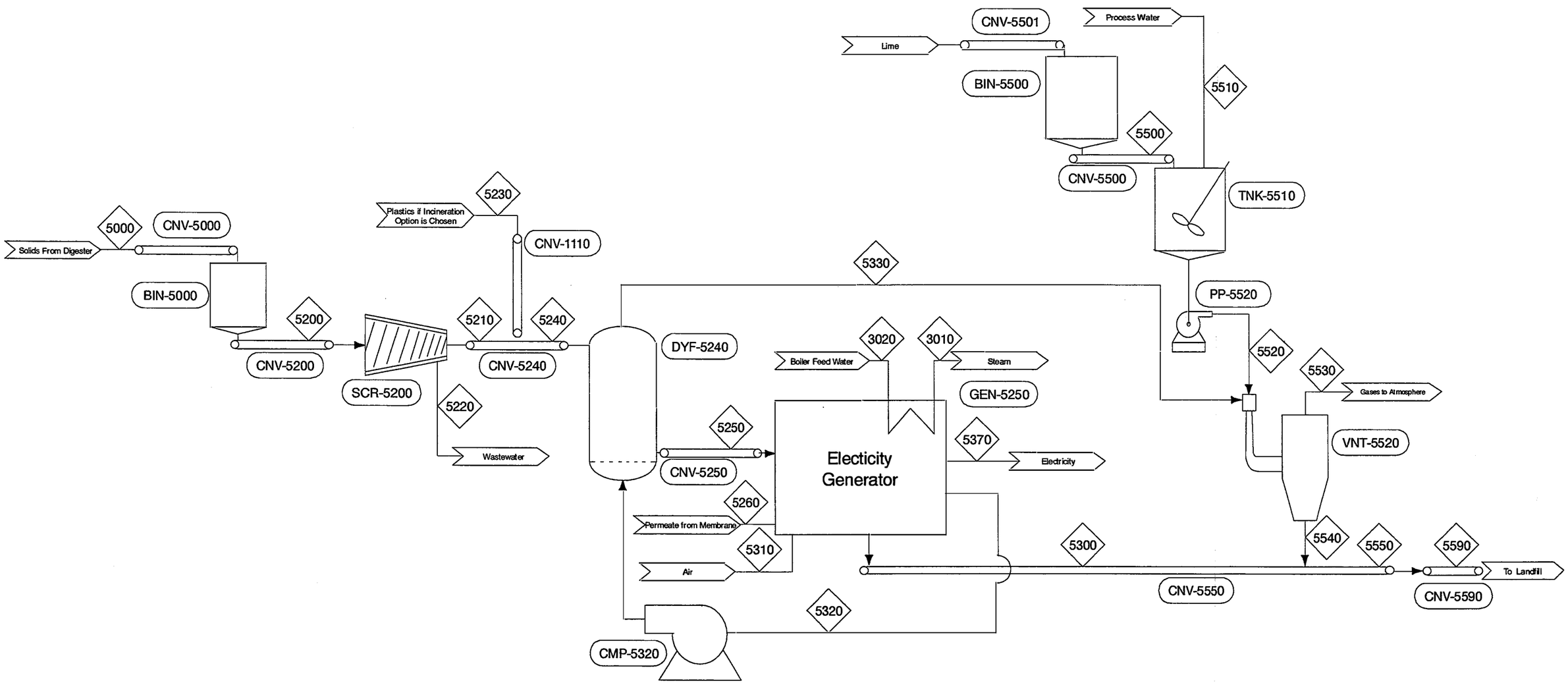

Figure 16. Solid Residue Processing Option D: Electricity Generation

Appendix B — Parameters used in ADAM's Material Balance Calculations

Parameter	Value	Worksheet Cell
Preprocessing Section		
Mechanical Sorting Option		
Glass Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBO11
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBO13
Fraction of Iron Removed	0.005	MATBAL.XLSBO15
Fraction of Aluminum Removed	0.005	MATBAL.XLSBO17
Fraction of Plastics Removed	0.03	MATBAL.XLSBO19
Fraction of Glass Removed	0.7	MATBAL.XLSBO21
Fraction of Other Non-Volatile Solids Removed	0.005	MATBAL.XLSBO23
Magnet #1		
Fraction of Moisture Removed	0.005	MATBAL.XLSBR11
Fraction of Volatile Solids Removed	0	MATBAL.XLSBR13
Fraction of Iron Removed	0.5	MATBAL.XLSBR15
Fraction of Aluminum Removed	0	MATBAL.XLSBR17
Fraction of Plastics Removed	0	MATBAL.XLSBR19
Fraction of Glass Removed	0.01	MATBAL.XLSBR21
Fraction of Other Non-Volatile Solids Removed	0	MATBAL.XLSBR23
Hammer Crusher: Temperature Rise	2.5°C	MATBAL.XLSBR29
Hammer Mill: Temperature Rise	2.5°C	MATBAL.XLSBR31

Parameter	Value	Worksheet Cell
Course Disk Screen		
Fraction of Moisture Removed	0.6	MATBAL.XLSBU11
Fraction of Volatile Solids Removed	0.6	MATBAL.XLSBU13
Fraction of Iron Removed	0.05	MATBAL.XLSBU15
Fraction of Aluminum Removed	0.05	MATBAL.XLSBU17
Fraction of Plastics Removed	0.95	MATBAL.XLSBU19
Fraction of Glass Removed	0.05	MATBAL.XLSBU21
Fraction of Other Non-Volatile Solids Removed	0.02	MATBAL.XLSBU23
Density of Stream 1090	590 kg/m3	MATBAL.XLSBU27
Density of Stream 1120	590 kg/m3	MATBAL.XLSBU29
Wet Trommel		
Percent Moisture in Entering Stream	50%	MATBAL.XLSBL41
Fraction of Moisture in Plastics Stream	0.15	MATBAL.XLSBL43
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBL45
Fraction of Iron Removed	0.5	MATBAL.XLSBL47
Fraction of Aluminum Removed	0.5	MATBAL.XLSBL49
Fraction of Plastics Removed	1	MATBAL.XLSBL51
Fraction of Glass Removed	0.9	MATBAL.XLSBL53
Fraction of Other Non-Volatile Solids Removed	0.3	MATBAL.XLSBL55
Temperature of Process Water	20°C	MATBAL.XLSBO31
Density of Plastics	320 kg/m3	MATBAL.XLSBO33

Parameter	Value	Worksheet Cell
Can Disk Screen		
Fraction of Moisture Removed	0.6	MATBAL.XLSBO41
Fraction of Volatile Solids Removed	0.6	MATBAL.XLSBO43
Fraction of Iron Removed	1	MATBAL.XLSBO45
Fraction of Aluminum Removed	1	MATBAL.XLSBO47
Fraction of Plastics Removed	0.2	MATBAL.XLSBO49
Fraction of Glass Removed	0.1	MATBAL.XLSBO51
Fraction of Other Non-Volatile Solids Removed	0.2	MATBAL.XLSBO53
Magnet #2		
Fraction of Moisture Removed	0.05	MATBAL.XLSBR41
Fraction of Volatile Solids Removed	0	MATBAL.XLSBR43
Fraction of Iron Removed	1	MATBAL.XLSBR45
Fraction of Aluminum Removed	0	MATBAL.XLSBR47
Fraction of Plastics Removed	0	MATBAL.XLSBR49
Fraction of Glass Removed	0.05	MATBAL.XLSBR51
Fraction of Other Non-Volatile Solids Removed	0	MATBAL.XLSBR53
Eddy Current Separator		
Fraction of Moisture Removed	0.05	MATBAL.XLSBU37
Fraction of Volatile Solids Removed	0	MATBAL.XLSBU39
Fraction of Iron Removed	0.2	MATBAL.XLSBU41
Fraction of Aluminum Removed	0.75	MATBAL.XLSBU43
Fraction of Plastics Removed	0.05	MATBAL.XLSBU45
Fraction of Glass Removed	0.05	MATBAL.XLSBU47
Fraction of Other Non-Volatile Solids Removed	0.05	MATBAL.XLSBU49
Density of Iron	7860 kg/m^3	MATBAL.XLSBU53
Density of Aluminum	2702 kg/m^3	MATBAL.XLSBU55
Density of Stream 1190	1000 kg/m^3	MATBAL.XLSBU57

Parameter	Value	Worksheet Cell
Fine Disk Screen		
Fraction of Moisture Removed	0.6	MATBAL.XLSBL63
Fraction of Volatile Solids Removed	0.6	MATBAL.XLSBL65
Fraction of Iron Removed	0.05	MATBAL.XLSBL67
Fraction of Aluminum Removed	0.05	MATBAL.XLSBL69
Fraction of Plastics Removed	1	MATBAL.XLSBL71
Fraction of Glass Removed	0.3	MATBAL.XLSBL73
Fraction of Other Non-Volatile Solids Removed	0.5	MATBAL.XLSBL75
Air Stoner		
Mass of Air to Mass of Feed Ratio	10	MATBAL.XLSBO59
Fraction of Moisture Removed	0.9	MATBAL.XLSBO61
Fraction of Volatile Solids Removed	0.05	MATBAL.XLSBO63
Fraction of Iron Removed	0	MATBAL.XLSBO65
Fraction of Aluminum Removed	0	MATBAL.XLSBO67
Fraction of Plastics Removed	0.75	MATBAL.XLSBO69
Fraction of Glass Removed	0.1	MATBAL.XLSBO71
Fraction of Other Non-Volatile Solids Removed	0.9	MATBAL.XLSBO73
Air Knife		
Mass of Air to Mass of Feed Ratio	10	MATBAL.XLSBR59
Fraction of Moisture Removed	0.9	MATBAL.XLSBR61
Fraction of Volatile Solids Removed	0	MATBAL.XLSBR63
Fraction of Iron Removed	0.95	MATBAL.XLSBR65
Fraction of Aluminum Removed	0.95	MATBAL.XLSBR67
Fraction of Plastics Removed	0.75	MATBAL.XLSBR69
Fraction of Glass Removed	0.8	MATBAL.XLSBR71
Fraction of Other Non-Volatile Solids Removed	0.9	MATBAL.XLSBR73

Parameter	Value	Worksheet Cell
Density of Rejects	961 kg/m3	MATBAL.XLSBL79
Density of Stream 1350	590 kg/m3	MATBAL.XLSBO77
Density of Stream 1450	590 kg/m3	MATBAL.XLSBO79
Density of Process Water	1000 kg/m3	MATBAL.XLSBO105
Molecular Weights		
Methane	16.04	MATBAL.XLSBR119
Hydrogen Sulfide	34.08	MATBAL.XLSBR121
Carbon Dioxide	44.01	MATBAL.XLSBR123
Water	18.02	MATBAL.XLSBR125
Methanol	32.04	MATBAL.XLSBR127
Average for Air	28.8	MATBAL.XLSBR129
Sulfur Dioxide	64.06	MATBAL.XLSBR131
Manual Sorting Option		
Glass Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBL319
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBL321
Fraction of Iron Removed	0.005	MATBAL.XLSBL323
Fraction of Aluminum Removed	0.005	MATBAL.XLSBL325
Fraction of Plastics Removed	0.03	MATBAL.XLSBL327
Fraction of Glass Removed	0.7	MATBAL.XLSBL329
Fraction of Non-Volatile Solids Removed	0.005	MATBAL.XLSBL331

Parameter	Value	Worksheet Cell
Iron Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBO319
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBO321
Fraction of Iron Removed	0.9	MATBAL.XLSBO323
Fraction of Aluminum Removed	0.005	MATBAL.XLSBO325
Fraction of Plastics Removed	0.03	MATBAL.XLSBO327
Fraction of Glass Removed	0.01	MATBAL.XLSBO329
Fraction of Non-Volatile Solids Removed	0.005	MATBAL.XLSBO331
Aluminum Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBR319
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBR321
Fraction of Iron Removed	0.1	MATBAL.XLSBR323
Fraction of Aluminum Removed	0.9	MATBAL.XLSBR325
Fraction of Plastics Removed	0.03	MATBAL.XLSBR327
Fraction of Glass Removed	0.03	MATBAL.XLSBR329
Fraction of Non-Volatile Solids Removed	0.005	MATBAL.XLSBR331
Plastic Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBL337
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBL339
Fraction of Iron Removed	0.005	MATBAL.XLSBL341
Fraction of Aluminum Removed	0.005	MATBAL.XLSBL343
Fraction of Plastics Removed	0.7	MATBAL.XLSBL345
Fraction of Glass Removed	0.1	MATBAL.XLSBL347
Fraction of Non-Volatile Solids Removed	0.005	MATBAL.XLSBL349

Parameter	Value	Worksheet Cell
Temperature Rise in Hammer Crusher and Mill	5°C	MATBAL.XLSBO335
Percent Moisture Leaving Trommel	50%	MATBAL.XLSBO339
Density of Stream 6120	1000	MATBAL.XLSBO345
Density of Stream 6140	1000	MATBAL.XLSBO347
Wet Trommel		
Fraction of Moisture Rejected	0.01	MATBAL.XLSBR337
Fraction of Volatile Solids Rejected	0.05	MATBAL.XLSBR339
Fraction of Iron Rejected	0.8	MATBAL.XLSBR341
Fraction of Aluminum Rejected	0.5	MATBAL.XLSBR343
Fraction of Plastics Rejected	0.1	MATBAL.XLSBR345
Fraction of Glass Rejected	0.6	MATBAL.XLSBR347
Fraction of Non-Volatile Solids Rejected	0.2	MATBAL.XLSBR349
Green Loading Option		
Reject Removal Station		
Fraction of Moisture Removed	0.01	MATBAL.XLSBL355
Fraction of Volatile Solids Removed	0.005	MATBAL.XLSBL357
Fraction of Iron Removed	0.9	MATBAL.XLSBL359
Fraction of Aluminum Removed	0.9	MATBAL.XLSBL361
Fraction of Plastics Removed	0.5	MATBAL.XLSBL363
Fraction of Glass Removed	0.8	MATBAL.XLSBL365
Fraction of Non-Volatile Solids Removed	0.4	MATBAL.XLSBL367
Temperature Rise in Hammer Crusher and Mill	5°C	MATBAL.XLSBO357
Density of Stream 7010	592 kg/m3	MATBAL.XLSBO361
Density of Stream 7030	592 kg/m3	MATBAL.XLSBO363

Parameter	Value	Worksheet Cell
Digestion Section		
Heat Capacity of Water	4.2 kJ/kg °C	MATBAL.XLSBR137
Enthalpy of 50 psig saturated steam	2743 kJ/kg	MATBAL.XLSBR139
Enthalpy of 50 psig saturated liquid	623.5 kJ/kg	MATBAL.XLSBR141
Lower Heating Value of Methane	51,905.3 kJ/kg	MATBAL.XLSBR143
Methane Density at STP	0.716 kg/m3	MATBAL.XLSBU125
Density of Stream 3060	1000 kg/m3	MATBAL.XLSBU129
Density of Stream 3080	1000 kg/m3	MATBAL.XLSBU131
Belt Filter Press After Digester		
Moisture Content of Filter Cake	0.3	MATBAL.XLSBO119
Fraction of Volatile Solids Removed	0.5	MATBAL.XLSBO121
Fraction of Iron Removed	0.95	MATBAL.XLSBO123
Fraction of Aluminum Removed	0.95	MATBAL.XLSBO125
Fraction of Plastics Removed	0.95	MATBAL.XLSBO127
Fraction of Biomass Removed	0.5	MATBAL.XLSBO129
Fraction of Glass Removed	0.95	MATBAL.XLSBO131
Fraction of Other Non Volatile Solids Removed	0.75	MATBAL.XLSBO133
Biogas Processing Section		
Biogas Filter		
Percent of Hydrogen Sulfide Removed	95%	MATBAL.XLSBL161
Maximum Fraction of Water in Fuel Stream	0.0005	MATBAL.XLSBL163
Flare		
Fraction of Incoming Gas that gets Flared	0	MATBAL.XLSBL169

Parameter	Value	Worksheet Cell
Membrane Separators to Produce SNG		
Volume Fraction Methane in SNG	0.95	MATBAL.XLSBL175
Percent of Methane Recovered	94.5%	MATBAL.XLSBL177
Fraction of Permeate Sidestream that is Recycled	0.5	MATBAL.XLSBL179
Membrane Separators to Produce Methanol		
Volume Fraction Methane in Gas entering Methanol Module	0.75	MATBAL.XLSBL185
Percent of Methane Recovered	94.0%	MATBAL.XLSBL187
Fraction of Permeate Sidestream that is Recycled	0.5	MATBAL.XLSBL189
Methanol Module		
Characteristic Production of Methanol	0.745 kg CH4/kg CH3OH	MATBAL.XLSBL195
Characteristic Module Size	16,900 kg CH4/day	MATBAL.XLSBL197
Exponent	-0.0956	MATBAL.XLSBL199
Density of Methanol	791.4 kg/m3	MATBAL.XLSBL201
Moles Methane Consumed / Mole of Methanol Produced	0.75	MATBAL.XLSBO195
Moles of Carbon Dioxide Consumed / Mole of Methanol Produced	0.25	MATBAL.XLSBO197
Moles of Water Consumed / Mole of Methanol Produced	0.5	MATBAL.XLSBO199
Gas Turbine Module		
Heating Value of Methane	11,953.6 kcal/kg	MATBAL.XLSBL209
Conversion of Watts to Calories / Second	0.239 W/(cal/s)	MATBAL.XLSBL213
Gas Turbine Efficiency	50%	MATBAL.XLSBL215
Combined Cycle Turbine Efficiency	75%	MATBAL.XLSBL217

Parameter	Value	Worksheet Cell
Mass Balances around Gas Turbine		
Percent of Excess Air Needed	50%	MATBAL.XLSBO205
Moles of Oxygen Needed / Mole of Methane	2	MATBAL.XLSBO207
Moles of Carbon Dioxide Produced / Mole of Methane	1	MATBAL.XLSBO209
Moles of Water Produced / Mole of Methane	2	MATBAL.XLSBO211
Moles of Oxygen Needed / Mole of H2S	1.5	MATBAL.XLSBO213
Moles of Sulfur Dioxide Produced / Mole of H2S	1	MATBAL.XLSBO215
Moles of Water Produced / Mole of H2S	1	MATBAL.XLSBL233
Molar Percentage of Air that is Oxygen	21%	MATBAL.XLSBO219
Solids Processing Section		
Density of Cake from Digester	961 kg/m3	MATBAL.XLSBL225
Incineration and Electricity Generation Options		
Screw Press		
Fraction of Volatile Solids lost to Wastewater	0.02	MATBAL.XLSBL231
Fraction of Non-Volatile Solids lost to Wastewater	0.02	MATBAL.XLSBL233
Fractional Moisture Content of Cake	0.2	MATBAL.XLSBL235
Fluid Bed Dryer		
Minimum Lower Heating Value in Incineration	10,458 kJ/kg	MATBAL.XLSBL241
Heat Content of Plastics	39,509 kJ/kg	MATBAL.XLSBL243
Heat Content of Dry and Ash Free Solids	23,241 kJ/kg	MATBAL.XLSBL245
Heat of Evaporation of Water	2588 kJ/kg	MATBAL.XLSBL247

Parameter	Value	Worksheet Cell
Incinerator		
Fraction of Biomass that is Uncombusted	0.2	MATBAL.XLSBO241
Fraction of Volatile Solids that are Uncombusted	0.2	MATBAL.XLSBO243
Fraction of Plastics that are Uncombusted	0.4	MATBAL.XLSBO245
Mass of Air needed/ Mass of Solid Fed	5	MATBAL.XLSBO247
Maximum Moisture Content of the Ash	0.05	MATBAL.XLSBO249
Efficiency	50%	MATBAL.XLSBO251
Temperature	250°C	MATBAL.XLSBO253
Density of Lime	3250 kg/m3	MATBAL.XLSBL259
Density of Stream 5520	1000 kg/m3	MATBAL.XLSBL261
Gas Clean Up		
Mass Gas / Mass Lime	500	MATBAL.XLSBL267
Moisture Fraction of Lime Stream being Mixed with Gas	0.9	MATBAL.XLSBL269
Fraction of the Water that is Evaporated in the Venturi Scrubber	0.25	MATBAL.XLSBL271
Density of the Combined Ash Stream	1185 kg/m3	MATBAL.XLSBL275
Density of the Plastics	320 kg/m3	MATBAL.XLSBL277
Composting		
Screw Press		
Fraction of Volatile Solids Lost to Waste Water	0.02	MATBAL.XLSBL285
Fraction of Non-Volatile Solids Lost to Waste Water	0.02	MATBAL.XLSBL287
Moisture Fraction of Cake	0.45	MATBAL.XLSBL289

Parameter	Value	Worksheet Cell
Trommel		
Fraction of Feed that is Rejected	0.2	MATBAL.XLSBL295
Density of Rejects	320 kg/m3	MATBAL.XLSBL297
Composting Pad		
Windrow Not Present		
Fraction of Water that is Evaporated	0.9	MATBAL.XLSBO285
Fraction of Volatile Solids that are Digested	0.6	MATBAL.XLSBO287
Windrow Present		
Fraction of Water that is Evaporated	0.9	MATBAL.XLSBO285
Fraction of Volatile Solids that are Digested	0.6	MATBAL.XLSBO287

Appendix C — Example

This example describes the methodology used to evaluate the economic feasibility of a municipal solid waste (MSW) anaerobic digestion facility. The MSW anaerobic digestion facility is proposed to alleviate a landfilling problem in an area producing 1,000 tons of MSW per day. Iron, aluminum, glass, and plastics are proposed to be separated manually and will be recycled. Synthetic natural gas (SNG) and compost are the proposed facility's products. A 10% discounted cash-flow rate of return over a 15-year plant life, while competing with the $50/ton tipping fee at the local landfill, is required.

First, the MSW feed is specified in columns A and B in the Input/Output (I/O) worksheet. The MSW generation rate is 1,000 tons per day, so 1,000 is entered into cell B6 in the I/O worksheet. The default values will be used to describe the composition because it is unknown. Each component's default is found by viewing the notes in the cells where the value is entered. All of the notes give specific values except glass, which gives a range. In this example, the middle of the range, 6%, is selected. The default density for MSW is present in that cell's note and is used in this example. Since MSW is the only feed to the facility, the flow rates of feeds two and three are set to zero. The completed feeds section is shown in Table C1.

Table C1: Feed Section of I/O Worksheet

Feeds	
Municipal Solid Waste	
Tons per Day (7 days / week)	1000
Mass Percent Total Solids	73.00%
Mass Percent Volatile Solids	48.00%
Mass Percent Iron	9.80%
Mass Percent Aluminum	1.10%
Mass Percent Plastics	4.50%
Mass Percent Glass	6.00%
Bulk Density (kg/m^3)	592
Feed #2 (Liquid)	
Tons per Day (7 days / week)	0
Mass Percent Total Solids	50.00%
Mass Percent Volatile Solids	30.00%
Bulk Density (kg/m^3)	1000
Feed #3 (Solid)	
Tons per Day (7 days / week)	0
Mass Percent Total Solids	26.00%
Mass Percent Volatile Solids	26.00%
Bulk Density (kg/m^3)	850

Manual separation is specified by entering "b" into cell D7. After allowing the spreadsheets to calculate, the preprocessing section looks like Table C2.

Table C2: MSW Preprocessing Section of I/O Worksheet

MSW Preprocessing Manual Separation	
Mechanical Separation (a),	
Manual Separation (b),	
or Green Loading (c)	b

The digester scheme is defined in the next section. A NRELHS digester with its default parameters will be examined. To choose an NRELHS digester, "a" is entered into cell F5. Then the NRELHS digester's parameters are set to their default values by clicking on the "Defaults" button. The digester section should then look like Table C3.

Table C3: Digester Section of I/O Worksheet

Digester NRELHS	
NRELHS (a) or REFCOM (b)	a
Solids Percent in Digester Influent	30%
Digester Residence Time (days)	17
Conversion of Volatile Solids to biogas	70%
Volatile Solids converted to Biomass	8%
N/A	1.00
Molar Fraction Methane in Dry Biogas	0.55
Molar Fraction Hydrogen Sulfide in Dry Biogas	0.02
Molar Fraction Carbon Dioxide in Dry Biogas	0.43
Temperature of the Digester (C)	37.0
Belt Filter Press is NOT Present (p to include)	n

The biogas processing option is chosen next. Production and sale of SNG is specified by entering "b" into cell H6. The section then appears as does Table C4.

Table C4: Biogas Processing Section of I/O Worksheet

Biogas Processing Sale of Synthetic Natural Gas	
Medium Btu Gas (a), Synthetic Natural Gas (b), Methanol (c) or Electrical Generation (d)	b
Not Applicable	a
Not Applicable	

The solid residue processing option is then selected. Production of compost is chosen by entering "b" into cell J6. The user must also decide if a windrow will be used. This example includes a windrow, so "y" is entered into cell J8. The user selects the plastics processing option in the next section. Because the proposed facility will send the separated plastics to a recycler, recycling is chosen by entering "b" in cell L6. After completion, the sections look like Table C5.

Table C5: Solid Residue Processing and Plastics Processing Sections of I/O Worksheet

Solid Residue Processing Composting		Plastics Processing Recycling	
Landfill (a), Compost (b), Incinerate (c), Incinerate with Generation of Electricity (d)	b	Landfill (a), Recycle (b), Incinerate (c) Can incinerate only if solid residue is set at c or d	b
Windrow is included (n if it is unnecessary)	y		

The values of the solvable costs and credits are input in the next section. The word "solve" is entered into cell N6, because the tipping fee is being solved for. The cost of solid waste disposal is known to be $50/ton ($55.10/1000 kg), so 55.10 is entered into cell N15. The word "lookup" is entered into the rest of the cells in column N that correspond to factors in column M, because the exact cost or value of the other items is unknown. If the solve column has an error in it (e.g., #NUM!, #DIV/0!), pressing the "Reset" button will eliminate that error. After completion, the section's appearance will be the same as Table C6.

Table C6: Solvable Costs and Credits Section of I/O Worksheet

Solvable Costs and Credits "lookup" if unknown, "solve" to solve for				
				Solution
MSW Tipping Fee ($/ton)	solve			
Synthetic Natural Gas ($/MMBtu)	lookup	$2.0000		
Compost ($/ton)	lookup	$10.0000		
Recyclable Iron ($/1000kg)	lookup	$5.5100		
Recyclable Aluminum ($/1000kg)	lookup	$551.2000		
Recyclable Plastic ($/1000kg)	lookup	$0.0000		
Recyclable Glass ($/1000kg)	lookup	$9.9200		
Solid Waste Disposal ($/1000kg)	$55.1000			
Waste Water Treatment ($/1000kg)	lookup	$0.2810		
Steam, 50 psi ($/1000kg)	lookup	$4.4000		
Electricity Used($/MWh)	lookup	$47.8000		
Process Water ($/1000kg)	lookup	$0.2900		

The "Other Factors" section is completed before modifying the financing section. The discounted cash flow rate of return (10%) and the plant life (15 years) are entered into cells W7 and W8, respectively. "Lookup" is entered into all of the other cells in the column W corresponding to factors in column V, because the exact values are unknown. The financing section can now be completed. The total capital investment should appear in cell U5. If an error is present, press the "Reset" button in cell M1 and the total capital investment will appear. The total capital investment may be incorrect, because the total capital investment is a function of the accounts receivable, which are dependent upon the tipping fees. In this example full equity financing will be assumed, so no input is necessary in column U. The two sections should have the same appearance as Table C7, with the exception of the total capital investment (cell U5) which may vary before the tipping fee is calculated.

Table C7: Financing and Other Factors Sections of the I/O Worksheet

Financing		Other Factors "lookup" if unknown		
Total Capital Investment	$44,074,783	Year	lookup	1993
		Chemical Engineering Index	lookup	358.0
Interest Paid in Year 1		Discount Cash Flow Rate of Return	10.00%	
Interest Paid in Year 2		Plant Life (years, 20 or fewer)	15	
Interest Paid in Year 3		Stream Factor	lookup	0.95
Interest Paid in Year 4		Unskilled Laborer Wage ($/hr)	lookup	$15.00
Interest Paid in Year 5		Operator Wage ($/hr)	lookup	$17.39
Interest Paid in Year 6		Supervisor Wage ($/hr)	lookup	$29.25
Interest Paid in Year 7		Federal Tax Rate	lookup	34.00%
Interest Paid in Year 8		State Tax Rate	lookup	4.55%
Interest Paid in Year 9		Rate of Inflation	lookup	3.50%
Interest Paid in Year 10				
Interest Paid in Year 11				
Interest Paid in Year 12				
Interest Paid in Year 13				
Interest Paid in Year 14				
Interest Paid in Year 15				

The input for the model is now complete. The tipping fee is found to be $44.65/ton by pressing the "Solve for Unknown" button. The solvable costs and credits section now looks like Table C8.

Table C8: Solvable Costs and Credits Section of the I/O Worksheet after Model has been Solved

Solvable Costs and Credits "lookup" if unknown, "solve" to solve for			Solution
MSW Tipping Fee ($/ton)	solve		$44.65
Synthetic Natural Gas ($/MMBtu)	lookup	$2.0000	
Compost ($/ton)	lookup	$10.0000	
Recyclable Iron ($/1000kg)	lookup	$5.5100	
Recyclable Aluminum ($/1000kg)	lookup	$551.2000	
Recyclable Plastic ($/1000kg)	lookup	$0.0000	
Recyclable Glass ($/1000kg)	lookup	$9.9200	
Solid Waste Disposal ($/1000kg)	$55.1000		
Waste Water Treatment ($/1000kg)	lookup	$0.2810	
Steam, 50 psi ($/1000kg)	lookup	$4.4000	
Electricity Used($/MWh)	lookup	$47.8000	
Process Water ($/1000kg)	lookup	$0.2900	

The results section looks like Table C9, and the model simulation summary is on the following page.

Table C9: Results Section of the I/O Worksheet after Model has been Solved

Results	
Synthetic Natural Gas Production (MMBtu/yr)	1,495,289
Compost Production (ton/yr)	90,332
Biogas Production (scf/day)	8,858,210
Methane Production (scf/day)	4,570,250
Gross Methane Yield (scf CH4/lb VS)	4.862
Volume CH4/Volume Reactor/day	4.78
VS loading Rate (lb VS/cf day)	0.984
Landfill Life Multiplier	7.8

MSWD Model Simulation Summary

Model Input

MSW Preprocessing Option: **Manual Separation**

Digester: **NRELHS**

Biogas Processing Option Chosen: **Sale of Synthetic Natural Gas**

Solid Residue Processing Option: **Composting**

Plastics Processing Option: **Recycling**

MSW Specifications

Tons per Day:	**1000**
Mass Percent Total Solids:	**73.0%**
Mass Percent Volatile Solids:	**48.0%**
Mass Percent Iron:	**9.8%**
Mass Percent Aluminum:	**1.1%**
Mass Percent Plastics:	**4.5%**
Mass Percent Glass:	**6.0%**

Liquid Waste Specifications

Tons per Day:	**N/A**
Mass Percent Total Solids:	**N/A**
Mass Percent Volatile Solids:	**N/A**

Solid Waste Specifications

Tons per Day:	**N/A**
Mass Percent Total Solids:	**N/A**
Mass Percent Volatile Solids:	**N/A**

Digester Specifications

Solids Percent in Digester Influent:	**30%**
Digester Residence Time (days):	**17**
Volatile Solids Converted to Biogas:	**70%**
Molar Fraction Methane in Dry Biogas:	**0.55**
Molar Fraction Hydrogen Sulfide in Dry Biogas:	**0.02**
Molar Fraction Carbon Dioxide in Dry Biogas:	**0.43**
Molar Fraction Water in Biogas:	**0.06**

Belt Filter Press is not Present

Credits

MSW Tipping Fee ($/ton)	**See Results**
Feed #2 Tipping Fee ($/ton)	**N/A**
Feed #3 Tipping Fee ($/ton)	**N/A**
Synthetic Natural Gas ($/MMBtu)	**$2.00**
Compost ($/ton)	**$10.00**
Recyclable Iron ($/1000kg)	**$5.51**
Recyclable Aluminum ($/1000kg)	**$551.00**
Recyclable Plastic ($/1000kg)	**$0.00**
Recyclable Glass ($/1000kg)	**$9.92**

Costs

Solid Waste Disposal ($/1000kg)	**$55.1000**
Waste Water Treatment ($/1000kg)	**$0.2810**
50 psi Steam ($/1000kg)	**$4.4000**
Electricity Used($/MWh)	**$47.8000**
Process Water ($/1000kg)	**$0.2900**
Lime ($/1000kg)	**N/A**
Total Interest Paid:	**$0**

Other Factors

Discount Cash Flow Rate of Return	**10.00%**
Plant Life (years)	**15**
Stream Factor	**0.95**
Federal Tax Rate	**34.00%**
State Tax Rate	**4.55%**
Inflation Rate	**3.50%**

Model Results

MSW Tipping Fee ($/ton)	**$44.60**
Total Capital Investment:	**$47,100,000**
Synthetic Natural Gas Production (MMBtu/yr)	**1,495,000**
Compost Production (ton/yr)	**90,300**
Biogas Production (scf/day)	**8,860,000**
Methane Production (scf/day)	**4,570,000**
Gross Methane Yield (scf CH4/lb VS)	**4.86**
Volume CH4/Volume Reactor/day	**4.78**
VS loading Rate (lb VS/cf day)	**0.984**
Landfill Life Multiplier	**7.8**

In some cases it may be possible to use other feeds with the MSW to increase the output of the facility. For example, a 50 ton/day manure feed from a small feedlot is available to the facility. It is 10% solids (7.5% volatile solids), has a density of 1000 kg/m^3, and does not need to be preprocessed before entering the digester. Its current tipping fee is only $20/ton. The use of this manure is evaluated by entering its specifications as feed #3. The completed feeds section looks like Table C10.

Table C10: Case Study Data Entered into Feeds Section of I/O Worksheet

Feeds	
Municipal Solid Waste	
Tons per Day (7 days / week)	1000
Mass Percent Total Solids	73.00%
Mass Percent Volatile Solids	48.00%
Mass Percent Iron	9.80%
Mass Percent Aluminum	1.10%
Mass Percent Plastics	4.50%
Mass Percent Glass	6.00%
Bulk Density (kg/m^3)	592
Feed #2 (Liquid)	
Tons per Day (7 days / week)	0
Mass Percent Total Solids	50.00%
Mass Percent Volatile Solids	30.00%
Bulk Density (kg/m^3)	1000
Feed #3 (Solid)	
Tons per Day (7 days / week)	50
Mass Percent Total Solids	10.00%
Mass Percent Volatile Solids	7.50%
Bulk Density (kg/m^3)	1000

The tipping fee of the manure is entered in cell N8, causing the Solvable Costs and Credits section to look like Table C11.

Table C11: Case Study Data Entered into Solvable Costs and Credits Section of I/O Worksheet

Solvable Costs and Credits "lookup" if unknown, "solve" to solve for			Solution
MSW Tipping Fee ($/ton)	solve		
Feed #3 Tipping Fee ($/ton)	$20.0000		
Synthetic Natural Gas ($/MMBtu)	lookup	$2.0000	
Compost ($/ton)	lookup	$10.0000	
Recyclable Iron ($/1000kg)	lookup	$5.5100	
Recyclable Aluminum ($/1000kg)	lookup	$551.2000	
Recyclable Plastic ($/1000kg)	lookup	$0.0000	
Recyclable Glass ($/1000kg)	lookup	$9.9200	
Solid Waste Disposal ($/1000kg)	$55.1000		
Waste Water Treatment ($/1000kg)	lookup	$0.2810	
Steam, 50 psi ($/1000kg)	lookup	$4.4000	
Electricity Used($/MWh)	lookup	$47.8000	
Process Water ($/1000kg)	lookup	$0.2900	

The MSW tipping fee is then solved for by pressing the "Solve for Unknown" button. The simulation summary, on the following page, shows that the tipping fee is $44.16/ton, which is lower than the tipping fee of $44.65/ton without the manure.

MSWD Model Simulation Summary

Model Input

MSW Preprocessing Option: **Manual Separation**

Digester: **NRELHS**

Biogas Processing Option Chosen: **Sale of Synthetic Natural Gas**

Solid Residue Processing Option: **Composting**

Plastics Processing Option: **Recycling**

MSW Specifications

Tons per Day:	**1000**
Mass Percent Total Solids:	**73.0%**
Mass Percent Volatile Solids:	**48.0%**
Mass Percent Iron:	**9.8%**
Mass Percent Aluminum:	**1.1%**
Mass Percent Plastics:	**4.5%**
Mass Percent Glass:	**6.0%**

Liquid Waste Specifications

Tons per Day:	**N/A**
Mass Percent Total Solids:	**N/A**
Mass Percent Volatile Solids:	**N/A**

Solid Waste Specifications

Tons per Day:	**50**
Mass Percent Total Solids:	**10%**
Mass Percent Volatile Solids:	**8%**

Digester Specifications

Solids Percent in Digester Influent:	**30%**
Digester Residence Time (days):	**17**
Volatile Solids Converted to Biogas:	**70%**
Molar Fraction Methane in Dry Biogas:	**0.55**
Molar Fraction Hydrogen Sulfide in Dry Biogas:	**0.02**
Molar Fraction Carbon Dioxide in Dry Biogas:	**0.43**
Molar Fraction Water in Biogas:	**0.06**

Belt Filter Press is not Present

Credits

MSW Tipping Fee ($/ton)	**See Results**
Feed #2 Tipping Fee ($/ton)	**N/A**
Feed #3 Tipping Fee ($/ton)	**$20.00**
Synthetic Natural Gas ($/MMBtu)	**$2.00**
Compost ($/ton)	**$10.00**
Recyclable Iron ($/1000kg)	**$5.51**
Recyclable Aluminum ($/1000kg)	**$551.00**
Recyclable Plastic ($/1000kg)	**$0.00**
Recyclable Glass ($/1000kg)	**$9.92**

Costs

Solid Waste Disposal ($/1000kg)	**$55.1000**
Waste Water Treatment ($/1000kg)	**$0.2810**
50 psi Steam ($/1000kg)	**$4.4000**
Electricity Used($/MWh)	**$47.8000**
Process Water ($/1000kg)	**$0.2900**
Lime ($/1000kg)	**N/A**
Total Interest Paid:	**$0**

Other Factors

Discount Cash Flow Rate of Return	**10.00%**
Plant Life (years)	**15**
Stream Factor	**0.95**
Federal Tax Rate	**34.00%**
State Tax Rate	**4.55%**
Inflation Rate	**3.50%**

Model Results

MSW Tipping Fee ($/ton)	**$44.20**
Total Capital Investment:	**$47,600,000**
Synthetic Natural Gas Production (MMBtu/yr)	**1,507,000**
Compost Production (ton/yr)	**91,400**
Biogas Production (scf/day)	**8,930,000**
Methane Production (scf/day)	**4,610,000**
Gross Methane Yield (scf CH4/lb VS)	**4.86**
Volume CH4/Volume Reactor/day	**4.78**
VS loading Rate (lb VS/cf day)	**0.982**
Landfill Life Multiplier	**8.0**

The lowest manure tipping fee allowable, while keeping the MSW tipping fee at $44.65, can be found by changing the solvable costs and credits section. The MSW tipping fee is set at $44.65/ton and "solve" is entered for the Feed #3 tipping fee. The section then looks like Table C12.

Table C12: Solvable Costs and Credits Section of I/O Worksheet

Solvable Costs and Credits "lookup" if unknown, "solve" to solve for			Solution
MSW Tipping Fee ($/ton)	$44.65		
Feed #3 Tipping Fee ($/ton)	solve		
Synthetic Natural Gas ($/MMBtu)	lookup	$2.0000	
Compost ($/ton)	lookup	$10.0000	
Recyclable Iron ($/1000kg)	lookup	$5.5100	
Recyclable Aluminum ($/1000kg)	lookup	$551.2000	
Recyclable Plastic ($/1000kg)	lookup	$0.0000	
Recyclable Glass ($/1000kg)	lookup	$9.9200	
Solid Waste Disposal ($/1000kg)	$55.1000		
Waste Water Treatment ($/1000kg)	lookup	$0.2810	
50 psi Steam ($/1000kg)	lookup	$4.4000	
Electricity Used($/MWh)	lookup	$47.8000	
Process Water ($/1000kg)	lookup	$0.2900	

The cost of Feed #3 is then solved for by pressing the "Solve for the Unknown" button. The tipping fee is found to be $10.23. The model simulation summary is on the following page.

MSWD Model Simulation Summary

Model Input

MSW Preprocessing Option: **Manual Separation**

Digester: **NRELHS**

Biogas Processing Option Chosen: **Sale of Synthetic Natural Gas**

Solid Residue Processing Option: **Composting**

Plastics Processing Option: **Recycling**

MSW Specifications

Tons per Day:	**1000**
Mass Percent Total Solids:	**73.0%**
Mass Percent Volatile Solids:	**48.0%**
Mass Percent Iron:	**9.8%**
Mass Percent Aluminum:	**1.1%**
Mass Percent Plastics:	**4.5%**
Mass Percent Glass:	**6.0%**

Liquid Waste Specifications

Tons per Day:	**N/A**
Mass Percent Total Solids:	**N/A**
Mass Percent Volatile Solids:	**N/A**

Solid Waste Specifications

Tons per Day:	**50**
Mass Percent Total Solids:	**10%**
Mass Percent Volatile Solids:	**8%**

Digester Specifications

Solids Percent in Digester Influent:	**30%**
Digester Residence Time (days):	**17**
Volatile Solids Converted to Biogas:	**70%**
Molar Fraction Methane in Dry Biogas:	**0.55**
Molar Fraction Hydrogen Sulfide in Dry Biogas:	**0.02**
Molar Fraction Carbon Dioxide in Dry Biogas:	**0.43**
Molar Fraction Water in Biogas:	**0.06**

Belt Filter Press is not Present

Credits

MSW Tipping Fee ($/ton)	**$44.65**
Feed #2 Tipping Fee ($/ton)	**N/A**
Feed #3 Tipping Fee ($/ton)	**See Results**
Synthetic Natural Gas ($/MMBtu)	**$2.00**
Compost ($/ton)	**$10.00**
Recyclable Iron ($/1000kg)	**$5.51**
Recyclable Aluminum ($/1000kg)	**$551.00**
Recyclable Plastic ($/1000kg)	**$0.00**
Recyclable Glass ($/1000kg)	**$9.92**

Costs

Solid Waste Disposal ($/1000kg)	**$55.1000**
Waste Water Treatment ($/1000kg)	**$0.2810**
50 psi Steam ($/1000kg)	**$4.4000**
Electricity Used($/MWh)	**$47.8000**
Process Water ($/1000kg)	**$0.2900**
Lime ($/1000kg)	**N/A**
Total Interest Paid:	**$0**

Other Factors

Discount Cash Flow Rate of Return	**10.00%**
Plant Life (years)	**15**
Stream Factor	**0.95**
Federal Tax Rate	**34.00%**
State Tax Rate	**4.55%**
Inflation Rate	**3.50%**

Model Results

Feed #3 Tipping Fee ($/ton)	**$10.20**
Total Capital Investment:	**$47,600,000**
Synthetic Natural Gas Production (MMBtu/yr)	**1,507,000**
Compost Production (ton/yr)	**91,400**
Biogas Production (scf/day)	**8,930,000**
Methane Production (scf/day)	**4,610,000**
Gross Methane Yield (scf CH4/lb VS)	**4.86**
Volume CH4/Volume Reactor/day	**4.78**
VS loading Rate (lb VS/cf day)	**0.982**
Landfill Life Multiplier	**8.0**

Appendix D — References

(1) Legrand, R.; Todd, T.M. (August 1990). *Systems Analysis of Municipal Solid Waste Biogasification*. US DOE/SERI Contract No. XL-8-18036. Work performed by Reynolds, Smith and Hills, Inc., Jacksonville, Florida.

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13. ABSTRACT *(Maximum 200 words)*

The Anaerobic Digestion Analysis Model (ADAM) was developed to help investigators perform preliminary economic analyses of anaerobic digestion processes. It can estimate the economic performance of several different user-defined waste digestion process configurations. The model can predict required feedstock tipping fees, product selling prices, utility rates, and raw material unit costs.

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