# RNG-CCS model for "Niche Markets for $CO_2$ Removal and Sequestration from Renewable Natural Gas Production in California"


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## 1 Summary

This document reflects the model in commit `8034c64`. The AMPL model is in `codigestion_model.mod`. We detail a model whose boundary span from biomass residue collection to $CO_2$ sequestration and $CH_4$ pipeline injection. The model codigests feedstocks other than landfill gas. For parsimony, we omit unit conversions present in the actual AMPL model.

## 2 Model Formulation

### 2.1 Notation

Sets are as follows:

| | |
|---|---|
| $f$ | Facilities |
| $l \in f$ | Landfills, a subset of facilities |
| $c \in f$ | Codigesters, a subset of facilities |
| $t$ | Feedstock type |
| $g \in t$ | Landfill gas, a subset of feedstock type |
| $s \in t$ | Set of codigestion types, subset of feedstock type |
| | $s = \{$Wastewater, Crop, Manure, MSW$\}$ |
| $i$ | Sequestration sites |
| $s$ | Feedstock source |
| $(s, f)$ | Feedstock source and facility pairs under 50 miles |
| $(f, i)$ | Facility and sequestration site pairs under 50 miles |

Parameters are as follows:

| | |
|---|---|
| **Facilities** | |
| $\text{pipe\_vc}_f$ | RNG pipeline fixed cost at facility $f$ |
| $\text{pipe\_vc}_f$ | RNG pipeline variable cost at facility $f$ |
| $\text{lmop}_l$ | Landfill collecting variable cost at landfill $l$ |
| **Sequestration sites** | |
| $\text{injection\_fc}_i$ | $CO_2$ injection fixed cost at sequestration site $i$ |
| $\text{injection\_vc}_i$ | $CO_2$ injection variable cost at sequestration site $i$ |
| $\text{capacity}_i$ | Sequestration site storage capacity at sequestration site $i$ |
| $\text{seismic}_i$ | 3-D seismic survey cost at sequestration site $i$ |
| **Type** | |
| $\text{ts}_t$ | Total solids % of feedstock type $t$ |
| $\text{vs}_t$ | Volatile solids % of feedstock type $t$ |
| $\text{ton}_t$ | Conversion to ton of feedstock type $t$ |
| $\text{biogas\_yield}_t$ | Biogas yield of feedstock type $t$ |
| $\text{c\_intensity}_t$ | Carbon intensity of resultant RNG from feedstock type $t$ |
| **Feedstock source & type** | |
| $\text{supply}_{s,t}$ | Feedstock quantity at source $s$ of type $t$ |
| **Valid source → facility pairs** | |
| $\text{fs\_dist}_{s,f}$ | Road distance between feedstock at location $s$ and facility $f$ |
| $\text{fs\_time}_{s,f}$ | Travel duration between feedstock at location $s$ and facility $f$ |
| $\text{per\_ton}_{s,f}$ | Per-ton cost from location $s$ to facility $f$ |
| **Valid facility → sequestration site pairs** | |
| $\text{rs\_dist}_{f,i}$ | Road distance between facility $f$ and sequestration site $i$ |
| $\text{rs\_time}_{f,i}$ | Travel duration between facility $f$ and sequestration site $i$ |

Scalars are as follows:

| | |
|---|---|
| **Cost (in 2019 $)** | |
| ad_fc_int | AD fixed cost intercept |
| $\text{ad\_fc\_slope}_1$ | AD fixed cost slope below threshold |
| $\text{ad\_fc\_slope}_2$ | AD fixed cost slope above threshold |
| ad_vc_int | AD variable cost intercept |
| $\text{ad\_vc\_slope}_1$ | AD variable cost slope below threshold |
| $\text{ad\_vc\_slope}_2$ | AD variable cost slope above threshold |
| up_fc_int | Biogas upgrading fixed cost intercept |
| $\text{up\_fc\_slope}_1$ | Biogas upgrading fixed cost slope below threshold |
| $\text{up\_fc\_slope}_2$ | Biogas upgrading fixed cost slope above threshold |
| up_vc_int | Biogas upgrading variable cost intercept |
| $\text{up\_vc\_slope}_1$ | Biogas upgrading variable cost slope below threshold |
| $\text{up\_vc\_slope}_2$ | Biogas upgrading variable cost slope above threshold |
| inj_fc_int | RNG injection fixed cost intercept |
| $\text{inj\_fc\_slope}_1$ | RNG injection fixed cost slope below threshold |
| $\text{inj\_fc\_slope}_2$ | RNG injection fixed cost slope above threshold |
| inj_vc_int | RNG injection variable cost intercept |
| $\text{inj\_vc\_slope}_1$ | RNG injection variable cost slope below threshold |
| $\text{inj\_vc\_slope}_2$ | RNG injection variable cost slope above threshold |
| $\text{comp\_fc\_int}_a$ | $CO_2$ compression to transporting pressure fixed cost intercept |

| | |
|---|---|
| comp_fc_slope$_{a1}$ | $CO_2$ compression to transporting pressure fixed cost slope below threshold |
| comp_fc_slope$_{a2}$ | $CO_2$ compression to transporting pressure fixed cost slope above threshold |
| comp_vc_int$_b$ | $CO_2$ compression to sequestration pressure variable cost intercept |
| comp_vc_slope$_{b1}$ | $CO_2$ compression to sequestration pressure variable cost slope below threshold |
| comp_vc_slope$_{b2}$ | $CO_2$ compression to sequestration pressure variable cost slope above threshold |
| comp_fc_slope$_{b1}$ | $CO_2$ compression to sequestration pressure fixed cost slope below threshold |
| comp_fc_slope$_{b2}$ | $CO_2$ compression to sequestration pressure fixed cost slope above threshold |
| comp_vc_int$_b$ | $CO_2$ compression to sequestration pressure variable cost intercept |
| comp_vc_slope$_{b1}$ | $CO_2$ compression to sequestration pressure variable cost slope below threshold |
| comp_vc_slope$_{b2}$ | $CO_2$ compression to sequestration pressure variable cost slope above threshold |
| cap_fc_int | $CO_2$ capture fixed cost intercept |
| cap_fc_slope$_1$ | $CO_2$ capture fixed cost slope below threshold |
| cap_fc_slope$_2$ | $CO_2$ capture fixed cost slope above threshold |
| cap_vc_int | $CO_2$ capture variable cost intercept |
| cap_vc_slope$_1$ | $CO_2$ capture variable cost slope below threshold |
| cap_vc_slope$_2$ | $CO_2$ capture variable cost slope above threshold |
| monitoring | $CO_2$ storage monitoring cost |
| fs_mi | Feedstock transport cost per mile |
| fs_hr | Feedstock transport cost per hour |
| rs_mi | $CO_2$ transport cost per mile |
| rs_hr | $CO_2$ transport cost per hour |
| **Revenues (\$/mmbtu)** | |
| lcfs | LCFS credit price |
| d5 | RIN D5 credit price |
| cellulosic_waiver | Cellulosic waiver price |
| 45q | 45Q tax credit |
| rng | RNG price |
| **Other assumptions** | |
| ch4_yield | $CH_4$ volume percentage in biogas |
| baseline_ci | Baseline carbon intensity of RNG |
| irr | Internal rate of return |
| life | Project lifetime |
| crf | Capital Recovery Factor $= \frac{\text{irr}\times(1+\text{irr})^{\text{life}}}{(1+\text{irr})^{\text{life}}-1}$ |
| electricity | Grid electricity carbon intensity |
| transport | Transport emissions |
| compression$_a$ | $CO_2$ compression work to transporting pressure |
| compression$_b$ | $CO_2$ compression work to sequestration pressure |

Decision variables are as follows:

| | |
|---|---|
| $ad_f$ | Binary if facility $f$ is active |
| $seq_i$ | Binary if sequestration site $i$ is active |
| $q\_feed_{s,f,t}$ | Quantity of feedstock from source $s$ of type $t$ delivered to facility $f$ |
| $q\_feedf_f$ | Total quantity of feedstock used at facility $f$ $= \sum_{s,t} q\_feed_{s,f,t}$ |
| $q\_feedf\_nowwtp_f$ | Total quantity of feedstock used at facility $f$, excluding wastewater $= \sum_{s,t} q\_feed_{s,f,t} - q\_feed_{s,f,t=\text{wastewater}} \times ton_{t=\text{wastewater}}$ |
| $q\_ch4_{t,f}$ | Quantity of $CH_4$ from feedstock type $t$ at facility $f$ $= \sum_s q\_feed_{s,f,t} \times ts_t \times vs_t \times biogas\_yield_t \times ch4\_yield$ |
| $q\_ch4f_f$ | Quantity of $CH_4$ produced at facility $f$ $\sum_t q\_ch4_{t,f}$ |
| $q\_captf_f$ | Quantity of $CO_2$ captured at facility $f$ $= \sum_{s,t} q\_feed_{s,f,t} \times ts_t \times vs_t \times biogas\_yield_t \times (1 - ch4\_yield)$ |
| $q\_co2seq_i$ | Quantity of $CO_2$ sequestered at sequestration site $i$ |
| $q\_co2trans_{f,i}$ | Quantity of $CO_2$ transported from facility $f$ to sequestration site $i$ |

## 2.2 Model

**Objective Function.** We aim to minimize net cost over the project lifetime:

$$\min \text{net cost} = \text{life} \times (\text{total cost} - \text{total revenue}) \tag{1}$$

where total cost is defined as:

$$
\begin{aligned}
\text{total cost} = &\sum_c \Big\{ (ad_c \times (\vec{\mathbf{Intc}} \times crf + pipe\_vc_c)) + \\
&\vec{\mathbf{ad\_fc}} \times q\_feedf\_nowwtp_c + \vec{\mathbf{ad\_vc}} \times q\_feedf_c + \\
&\vec{\mathbf{up\_inj}} \times q\_ch4f_c + \vec{\mathbf{comp\_capt}} \times q\_captf_c + \\
&lcfs \times compression \times electricity \times q\_captf_c \Big\} + \\
&\sum_l \Big\{ (ad_l \times (\vec{Intl}_l \times crf + pipe\_vc_l)) + \\
&\vec{\mathbf{up\_inj}} \times q\_ch4f_l + \vec{\mathbf{comp\_capt}} \times q\_captf_l + \\
&lcfs \times compression_a \times electricity \times q\_captf_l \Big\} + \\
&\sum_{s,f,t} \Big\{ (fs\_dist_{s,f} \times fs\_mi + fs\_time_{s,f} * fs\_hr) \times \frac{q\_feed_{s,f,t}}{fs\_truckload} + \\
&per\_ton_{s,f} \times q\_feed_{s,f,t} \Big\} + \\
&\sum_{f,i} \Big\{ (rs\_time_{f,i} \times rs\_hr + rs\_dist_{f,i} \times rs\_mi) \times \frac{q\_co2trans_{f,i}}{co2\_truckload} + \\
&lcfs \times transport \times q\_co2trans_{f,i} \times rs\_dist_{f,i} \Big\} + \\
&\sum_i \Big\{ (seq_i \times ((injection\_fc_i + seismic_i) \times crf + injection\_vc_i)) + \\
&\vec{\mathbf{comp\_mon}} \times q\_co2seq_i + lcfs \times compression_b \times electricity \times q\_co2seq_i \Big\}
\end{aligned} \tag{2}
$$

and total revenue is defined as:

$$\begin{aligned}\text{total revenue} = &\sum_c \Big\{\text{q\_ch4f}_c \times (\text{rng} + \text{d5})\Big\} + \sum_l \Big\{\text{q\_ch4f}_l \times (\text{rng} + \text{d5} + \text{cellulosic})\Big\} + \\ &\sum_{t,f} \Big\{\text{q\_ch4}_{t,f} \times [\text{lcfs} \times (\text{baseline\_ci} - \text{c\_intensity}_t)]\Big\} + \\ &\sum_i \Big\{\text{q\_co2seq}_i \times (\text{lcfs} + \text{45q})\Big\}\end{aligned} \tag{3}$$

We denote $\vec{\textbf{Intc}}$ to be a vector of all piecewise intercepts relevant to the total costs for codigesting facilities and $\vec{\textbf{Intl}}_l$ to be a vector of all piecewise intercepts relevant to the total costs for landfills:

$$\vec{\textbf{Intc}} = \begin{bmatrix} \text{ad\_fc\_int} \times \text{crf} \\ \text{ad\_vc\_int} \\ \text{up\_fc\_int} \times \text{crf} \\ \text{up\_vc\_int} \\ \text{inj\_fc\_int} \times \text{crf} \\ \text{inj\_vc\_int} \\ \text{comp\_fc\_int}_a \times \text{crf} \\ \text{comp\_vc\_int}_a \\ \text{cap\_fc\_int} \times \text{crf} \\ \text{cap\_vc\_int} \\ \text{pipe\_fc}_c \times \text{crf} \\ \text{pipe\_vc}_c \end{bmatrix} \qquad \vec{\textbf{Intl}}_l = \begin{bmatrix} \text{lmop}_l \\ \text{up\_fc\_int} \times \text{crf} \\ \text{up\_vc\_int} \\ \text{inj\_fc\_int} \times \text{crf} \\ \text{inj\_vc\_int} \\ \text{comp\_fc\_int}_a \times \text{crf} \\ \text{comp\_vc\_int}_a \\ \text{cap\_fc\_int} \times \text{crf} \\ \text{cap\_vc\_int} \\ \text{pipe\_fc}_l \times \text{crf} \\ \text{pipe\_vc}_l \end{bmatrix}$$

We denote $\vec{\textbf{ad\_fc}}$ and $\vec{\textbf{ad\_vc}}$ to be vectors of the piecewise slopes for fixed and variable costs for anaerobic digesters, taking on different values depending on the value of $\text{q\_feed}_{s,f,t}$.

$$\vec{\textbf{ad\_fc}} = \begin{bmatrix} \text{ad\_fc\_slope}_1 \\ \text{ad\_fc\_slope}_2 \end{bmatrix} \times \text{crf} \qquad \vec{\textbf{ad\_vc}} = \begin{bmatrix} \text{ad\_vc\_slope}_1 \\ \text{ad\_vc\_slope}_2 \end{bmatrix}$$

We denote $\vec{\textbf{up\_inj}}$ and $\vec{\textbf{comp\_capt}}$ to be vectors of the piecewise slopes for fixed and variable costs for upgrading and injection, and compression and $CO_2$ capture, respectively. Facilities take on different values within these vectors depending on the values of $\text{q\_captf}_f$ and $\text{q\_ch4f}_f$.

$$\vec{\textbf{up\_inj}} = \begin{bmatrix} (\text{up\_fc\_slope}_1 + \text{inj\_fc\_slope}_1) \times \text{crf} + \text{up\_vc\_slope}_1 + \text{inj\_vc\_slope}_1 \\ (\text{up\_fc\_slope}_2 + \text{inj\_fc\_slope}_2) \times \text{crf} + \text{up\_vc\_slope}_2 + \text{inj\_vc\_slope}_2 \end{bmatrix}$$

$$\vec{\textbf{comp\_capt}} = \begin{bmatrix} (\text{comp\_fc\_slope}_{a1} + \text{capt\_fc\_slope}_1) \times \text{crf} + \text{comp\_vc\_slope}_{a1} + \text{capt\_vc\_slope}_1 \\ (\text{comp\_fc\_slope}_{a2} + \text{capt\_fc\_slope}_2) \times \text{crf} + \text{comp\_vc\_slope}_{a2} + \text{capt\_vc\_slope}_2 \end{bmatrix}$$

We denote $\vec{\textbf{comp\_mon}}$ to be vectors of the piecewise slopes for fixed and variable costs of monitoring and compression cost at sequestration sites. Sequestration sites take on values within these vectors depending on the value of $\text{q\_co2seq}_i$.

$$\vec{\textbf{comp\_mon}} = \begin{bmatrix} \text{comp\_fc\_slope}_{b1} \times \text{crf} + \text{comp\_vc\_slope}_{b1} + \text{monitoring} \\ \text{comp\_fc\_slope}_{b2} \times \text{crf} + \text{comp\_vc\_slope}_{b2} + \text{monitoring} \end{bmatrix}$$

**Constraints**. The objective function is subject to:

Feedstock used is zero if the facility is not activated

$$\text{q\_feed}_{s,f,t} \le \text{supply}_{s,t} \times \text{ad}_f \tag{4}$$

Feedstock used cannot exceed available supply

$$\sum_{f} \text{q\_feed}_{s,f,t} = \text{supply}_{s,t} \tag{5}$$

$CO_2$ transported is equal to $CO_2$ captured

$$\sum_{i} \text{q\_co2trans}_{f,i} = \text{q\_captf}_{f} \tag{6}$$

$CO_2$ sequestered is equal to $CO_2$ transported

$$\sum_{f} \text{q\_co2trans}_{f,i} = \text{q\_co2seq}_{i} \tag{7}$$

$CO_2$ sequestered cannot be more than available capacity

$$\text{q\_co2seq}_{i} \leq \text{capacity}_{i} \times \text{seq}_{i} \tag{8}$$

Minimum sequestration volume

$$\text{q\_co2seq}_{i} \geq 25000 \times \text{seq}_{i} \tag{9}$$