

# Effective Use of Carbon Pricing on Climate Change Mitigation Projects: Analysis of Biogas Supply Chain to Substitute Liquefied-Petroleum Gas in Mexico

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## Supplementary Material

The parameters used by the model to demonstrate the applicability in the case study are presented as follows. The technologies to produce biogas are three (see **Table S1**): chamber-floating drum type biogas plant (TechA), digester floating drum type biogas holder (TechB) and fixed-dome type biogas plant (TechC), where the capital costs and biomass yield were calculated and obtained from literature [1,2]. The purification technologies (upgrade technology) are (see **Table S2**): pressure swing adsorption (PSA), high pressure water scrubbing (HPWS), organic physical scrubbing (OPS), chemical scrubbing process (CSP) and membrane separation (MS), where the capital cost and biogas yield are obtained from literature [3]. The economic, environmental and general parameters are tabulated in **Table S3** with their respective references. Finally, the demand of energy [4], digestate [5] and biomass availability [6–8] are showed in **Table S4**, and the selected technologies for 10% of energy demand in the case study are presented in **Table S5**.

**Table S1.** Capacity, capital cost and yield of production technologies for biogas.

| No.                                        | Capacity<br>(Nm <sup>3</sup> /month) | TechA            | TechB            | TechC          |
|--------------------------------------------|--------------------------------------|------------------|------------------|----------------|
|                                            |                                      | Capital cost (€) |                  |                |
| 1                                          | 35000                                | 86100            | 96950            | 70350          |
| 2                                          | 90000                                | 221400           | 249300           | 180900         |
| 3                                          | 180000                               | 442800           | 498600           | 361800         |
| 4                                          | 1000000                              | 2460000          | 2770000          | 2010000        |
| 5                                          | 1400000                              | 3444000          | 3878000          | 2814000        |
| 6                                          | 1800000                              | 4428000          | 4986000          | 3618000        |
| 7                                          | 2000000                              | 4920000          | 5540000          | 4020000        |
| Yield (Nm <sup>3</sup> ton <sup>-1</sup> ) |                                      |                  |                  |                |
|                                            |                                      | Manure           | Organic<br>Waste | Waste<br>Water |
|                                            |                                      | 80               | 103              | 40             |

**Table S2.** Capacity, capital cost and yield of upgrade technologies for biogas.

|                                           |                                      | PSA              | HPWS       | OPS        | CSP        | MS         |
|-------------------------------------------|--------------------------------------|------------------|------------|------------|------------|------------|
| No.                                       | Capacity<br>(Nm <sup>3</sup> /month) | Capital cost (€) |            |            |            |            |
| 1                                         | 20000                                | 152777.77        | 33888.88   | 133333.33  | 291666.66  | 183333.33  |
| 2                                         | 50000                                | 381944.44        | 84722.22   | 333333.33  | 729166.66  | 458333.33  |
| 3                                         | 100000                               | 763888.88        | 169444.44  | 666666.66  | 763888.88  | 347222.22  |
| 4                                         | 600000                               | 1833333.33       | 1666666.67 | 2000000.00 | 2166666.67 | 1833333.33 |
| 5                                         | 800000                               | 2444444.44       | 2222222.22 | 2666666.67 | 2888888.89 | 2444444.44 |
| 6                                         | 1000000                              | 3055555.56       | 2777777.78 | 3333333.33 | 3611111.11 | 3055555.56 |
| 7                                         | 1200000                              | 3666666.67       | 3333333.33 | 4000000.00 | 4333333.33 | 3666666.67 |
| Yield (Nm <sup>3</sup> Nm <sup>-3</sup> ) |                                      |                  |            |            |            |            |
|                                           |                                      | 0.65             | 0.68       | 0.60       | 0.62       | 0.65       |

**Table S3.** Economic parameters for case study.

| Parameter                    | Type                        | Value   | Units                             | Reference  |
|------------------------------|-----------------------------|---------|-----------------------------------|------------|
| $C_{i,f,t}^{Bm}$             | Manure                      |         |                                   |            |
|                              | Organic wastes              | 1       | € ton <sup>-1</sup>               | Supposed   |
|                              | Waste water                 |         |                                   |            |
| $C_{j,l}^{Fix,Prod\_tech}$   | See Table 3                 | -       | €                                 | [1]        |
| $C_{k,m}^{Fix,Pur\_tech}$    | See Table 3                 | -       | €                                 | [3]        |
| $C_{i,f,l,t}^{Trans,Bm}$     |                             |         |                                   |            |
| $C_{i,l,m,t}^{Trans,Bg}$     |                             |         | € km <sup>-1</sup>                |            |
| $C_{i,l,p,t}^{Trans,Bg}$     | All                         | 0.00875 | ton <sup>-1</sup> or €            | Calculated |
| $C_{k,m,p,t}^{Trans,Bgp}$    |                             |         | km <sup>-1</sup> Nm <sup>-3</sup> |            |
| $C_{i,l,q,t}^{Trans,Fr}$     |                             |         |                                   |            |
| $C_{i,j,t}^{Var,Prod\_tech}$ | Floating Drum               | 0.2     |                                   |            |
|                              | Floating Drum Biogas Holder | 0.18    | € Nm <sup>-3</sup>                | [1]        |
|                              | Fixed Dome                  | 0.24    |                                   |            |
|                              | PSA                         | 0.4     |                                   |            |
| $C_{m,k,t}^{Var,Pur\_tech}$  | HPWS                        | 0.13    |                                   |            |
|                              | OPS                         | 0.11    | € Nm <sup>-3</sup>                | [3]        |
|                              | CSP                         | 0.17    |                                   |            |
|                              | MS                          | 0.12    |                                   |            |
| $N$                          |                             | 10      | Years                             | Supposed   |
| $R_{k,p,t}^{Bgp}$            | -                           | 18.47   | € GJ <sup>-1</sup>                | [9]        |
| $R_{p,t}^{FFuel}$            | -                           | *18.47. | € GJ <sup>-1</sup>                | [9]        |
| $R_{i,q,t}^{Fr}$             | Manure                      |         |                                   |            |
|                              | Organic wastes              | 5.6     | € ton <sup>-1</sup>               | [10]       |
|                              | Waste water                 |         |                                   |            |

|          |     |      |   |          |
|----------|-----|------|---|----------|
| $\alpha$ | All | 0.10 | - | Supposed |
|----------|-----|------|---|----------|

\* the economic benefit is 60% of the price (i.e., 11.08 € GJ<sup>-1</sup>)

**Table S4.** Environmental and general parameters for case study.

| Parameter        | Value   | Units                                   | Reference  |
|------------------|---------|-----------------------------------------|------------|
| $E^{Use, FFuel}$ | 0.0652  | Ton CO <sub>2</sub> eq GJ <sup>-1</sup> | [11]       |
| $H^{Bgp}$        | 50      | GJ ton <sup>-1</sup>                    | Calculated |
| $H^{FFuel}$      | 46.1    | GJ ton <sup>-1</sup>                    | Calculated |
| $\rho^{Bg, N}$   | 0.00080 | ton m <sup>-3</sup>                     | Calculated |

**Table S5.** Demands and availability for case study.

| City                          | Energy<br>(GJ<br>/month) | Digestate<br>Ton/mont<br>h | Biomass Availability<br>(Ton/month) |                  |                |
|-------------------------------|--------------------------|----------------------------|-------------------------------------|------------------|----------------|
|                               |                          |                            | Manure                              | Organic<br>Waste | Waste<br>Water |
| Aguililla                     | 4332.76                  | 61.79                      | 8732.34                             | 225.00           | 0              |
| Apatzingán                    | 36459.34                 | 88.41                      | 6159.33                             | 2700.00          | 0              |
| Arteaga                       | 6293.46                  | 36.22                      | 11132.61                            | 210.00           | 0              |
| Coalcomán de Vázquez Pallares | 5243.32                  | 41.48                      | 10339.32                            | 210.00           | 13478.4        |
| Cotija                        | 5406.50                  | 19.59                      | 3154.41                             | 210.00           | 12960          |
| La Huacana                    | 9734.71                  | 80.55                      | 7260.33                             | 225.00           | 16588.8        |
| Huetamo                       | 11603.88                 | 87.40                      | 12624.60                            | 450.00           | 0              |
| Morelia                       | 223098.74                | 64.69                      | 3838.56                             | 2100.00          | 623790.72      |
| La Piedad                     | 29480.75                 | 35.89                      | 3428.22                             | 1500.00          | 103420.8       |
| Puruándiro                    | 4464.67                  | 154.33                     | 3072.60                             | 480.00           | 0              |
| Tanhuato                      | 4364.32                  | 84.53                      | 17134.05                            | 180.00           | 0              |
| Tepalcatepec                  | 6777.88                  | 160.52                     | 6769.83                             | 540.00           | 0              |
| Zamora                        | 55778.66                 | 77.68                      | 1544.01                             | 2550.00          | 144633.6       |
| Abasolo                       | 25866.94                 | 244.12                     | 3971.10                             | 450.00           | 31622.4        |
| San Miguel de Allende         | 48856.08                 | 111.28                     | 8532.75                             | 1350.00          | 46656          |
| Manuel Doblado                | 11039.29                 | 138.37                     | 6664.95                             | 255.00           | 9072           |

|                                               |           |        |          |          |           |
|-----------------------------------------------|-----------|--------|----------|----------|-----------|
| Dolores Hidalgo Cuna de la Independencia Nac. | 43243.19  | 116.60 | 11913.69 | 1050.00  | 45100.8   |
| León                                          | 448777.06 | 119.69 | 10622.64 | 14595.00 | 813006.72 |
| Pénjamo                                       | 42804.54  | 471.82 | 8624.94  | 2955.00  | 570.24    |
| Purísima del Rincón                           | 22685.24  | 70.22  | 3556.89  | 73.95    | 0         |
| Salvatierra                                   | 28539.49  | 115.45 | 7106.25  | 900.00   | 20736     |
| San Felipe                                    | 32155     | 292.73 | 14414.43 | 900.00   | 51425.28  |
| San Luis de la Paz                            | 34405.96  | 85.42  | 10578.78 | 975.00   | 42042.24  |
| Silao                                         | 53890.74  | 71.22  | 3714.51  | 1776.60  | 55676.16  |
| Valle de Santiago                             | 40559.27  | 272.23 | 3370.95  | 1800.00  | 28512     |
| Yuriria                                       | 19832.46  | 95.96  | 2104.50  | 420.00   | 31104     |
| Acatic                                        | 6120.62   | 55.50  | 15432.30 | 375.00   | 18144     |
| Arandas                                       | 21922.79  | 101.16 | 11460.09 | 1050.00  | 52358.4   |
| Atotonilco el Alto                            | 17193.46  | 113.38 | 5855.55  | 507.60   | 35251.2   |
| La Barca                                      | 18494.05  | 267.01 | 3034.86  | 1200.00  | 0         |
| Degollado                                     | 6106.12   | 54.70  | 6258.39  | 330.00   | 0         |
| Encarnación de Díaz                           | 15224.79  | 159.79 | 18311.79 | 405.00   | 0         |
| Guadalajara                                   | 415095.74 | 0.00   | 56.31    | 28483.95 | 41472     |
| Jesús María                                   | 5534.71   | 69.61  | 4366.02  | 345.00   | 2073.6    |
| San Miguel el Alto                            | 9369.98   | 37.11  | 17818.62 | 300.00   | 4665.6    |
| Tamazula de gordiano                          | 10915.34  | 74.51  | 6418.08  | 487.20   | 0         |
| Tepatitlán de Morelos                         | 40175.49  | 137.39 | 19803.30 | 1800.00  | 123379.2  |
| Tomatlán                                      | 10184.17  | 69.38  | 20470.47 | 450.00   | 22291.2   |
| Zapopan                                       | 378742.73 | 50.58  | 5460.57  | 22387.65 | 3209155.2 |
| Zapotlanejo                                   | 19478.81  | 55.87  | 8675.91  | 795.00   | 18144     |

**Table S6.** Selected technologies for 10% of energy demand in case study.

| City       | Production Technology | Upgrade Technology |
|------------|-----------------------|--------------------|
| Aguililla  | Tech.C1               | HPWS1              |
| Apatzingán | Tech.C3               | HPWS4              |

|                                               |         |       |
|-----------------------------------------------|---------|-------|
| Arteaga                                       | Tech.C1 | HPWS2 |
| Coalcomán de Vázquez Pallares                 | Tech.A3 | HPWS3 |
| Cotija                                        | Tech.C1 | HPWS2 |
| La Huacana                                    | Tech.C2 | HPWS2 |
| Huetamo                                       | Tech.C2 | HPWS3 |
| Morelia                                       | Tech.C6 | MS7   |
| La Piedad                                     | Tech.C3 | HPWS3 |
| TPuruándiro                                   | Tech.C1 | HPWS2 |
| Tanhuato                                      | Tech.C1 | HPWS1 |
| Tepalcatepec                                  | Tech.C2 | HPWS2 |
| Zamora                                        | Tech.C7 | HPWS4 |
| Abasolo                                       | Tech.C3 | HPWS3 |
| San Miguel de Allende                         | Tech.B4 | HPWS4 |
| Manuel Doblado                                | Tech.A3 | HPWS3 |
| Dolores Hidalgo Cuna de la Independencia Nac. | Tech.B4 | HPWS4 |
| León                                          | Tech.C7 | MS7   |
| Pénjamo                                       | Tech.B4 | HPWS4 |
| Purísima del Rincón                           | Tech.C5 | HPWS6 |
| Salvatierra                                   | Tech.C3 | HPWS3 |
| San Felipe                                    | Tech.B4 | HPWS4 |
| San Luis de la Paz                            | Tech.B4 | HPWS4 |
| Silao                                         | Tech.B4 | HPWS4 |
| Valle de Santiago                             | Tech.B4 | HPWS4 |
| Yuriria                                       | Tech.C3 | HPWS3 |
| Acatic                                        | Tech.A3 | HPWS3 |
| Arandas                                       | Tech.C3 | HPWS3 |
| Atotonilco el Alto                            | Tech.C3 | HPWS3 |
| La Barca                                      | Tech.A3 | HPWS3 |
| Degollado                                     | Tech.C3 | HPWS3 |
| Encarnación de Díaz                           | Tech.C3 | HPWS3 |
| Guadalajara                                   | Tech.C7 | MS7   |
| Jesús María                                   | Tech.C1 | HPWS1 |
| San Miguel el Alto                            | Tech.C2 | HPWS2 |
| Tamazula de gordiano                          | Tech.C2 | HPWS3 |
| Tepatitlán de Morelos                         | Tech.C3 | HPWS4 |
| Tomatlán                                      | Tech.C2 | HPWS2 |
| Zapopan                                       | Tech.C7 | MS7   |
| Zapotlanejo                                   | Tech.C6 | MS7   |

### Supplementary Material References

1. Yasar, A.; Nazir, S.; Rasheed, R.; Tabinda, A.B.; Nazar, M. Economic review of different designs of biogas plants at household level in Pakistan. *Renew. Sustain. Energy Rev.* **2017**, *74*,

221–229.

2. Scarlat, N.; Dallemand, J.-F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew. Energy* **2018**, *129*, 457–472.
3. Khan, I.; hafiz, mohd; Othman, M.H.; Hashim, H.; Matsuura, T.; Ismail, A.; Rezaei Dasht Arzhandi, M.; Wan Azelee, I. *Biogas as a renewable energy fuel – A review of biogas upgrading, utilisation and storage*; 2017; Vol. 150;.
4. SENER *Prospectiva de Gas Natural y Gas L.P 2014-2028*; México, 2014;
5. BIRF; AIF; IFC; MIGA; CIADI Banco Mundial Available online: <https://datos.bancomundial.org/indicador/AG.CON.FERT.ZS?locations=MX&view=chart>.
6. Instituto Nacional de Estadística y Geografía (México) *Anuario estadístico y geográfico de Jalisco 2016*; México, 2016;
7. Instituto Nacional de Estadística y Geografía (México) *Anuario estadístico y geográfico de Michoacán de Ocampo 2016*; México, 2016;
8. Instituto Nacional de Estadística y Geografía (México) *Anuario estadístico y geográfico de Guanajuato 2016*; México, 2016;
9. SENER L.P. Gas Outlook 2016 - 2030. **2016**.
10. Agency, E. *Partial Financial Impact Assessment of the introduction of a Quality Protocol for the production and use of anaerobic digestate*; Banbury, Oxon, 2009;
11. INECC *Factores de emisión para los diferentes tipos de combustibles fósiles y alternativos que se consumen en México*; México, D.F., 2014;