Energy crops applied to landfills: functional, environmental and costs analysis

Prof. Ing. Alberto Pivato

DII - Department of Industrial Engineering, University of Padova, via Marzolo n 9, 35131 Padova, Italy

alberto.pivato@unipd.it
Work groups and aims

Different steps

Scenario zero (Reference scenario) definition
Alternative scenarios → present study

Main aim

Strategies for reducing “landfill gate fee”
(unit payment for landfill life cycle service)

Specific aims

- Evaluate the application of energy crops to landfill
- Compare energy crops solutions
- Suggest solutions able to reduce landfill cost, producing energy and increasing the environmental quality of the site
Methodology

Definition of criteria to use in the study

1) Economic
2) Energetic
3) Environmental

Define landfill scenarios to compare with the “scenario zero”

1) Energetic maximization scenario
2) Leachate phytodepuration scenario
3) Environmental compensation scenario
4) Combination scenario

Multi-Criteria Analysis
Criteria definition - Economic criteria

- Evaluate the total cost of the scenario
- Consideration of all the landfill phases
- $x_{ECONOMIC} = \text{COST}_{\text{REFERENCE}} - \text{COST}_{\text{SCENARIO}}$
Criteria definition - Energetic criteria

- Evaluate the energetic net gain (unit of measure: Joule)

\[ x_{\text{ENERGETIC}} = \text{ENERGY}_{\text{SCENARIO}} - \text{ENERGY}_{\text{REFERENCE}} \]

**ENERGETIC NET GAIN** = **ENERGETIC OUTPUTS** - **ENERGETIC INPUTS**

Lower Heating value of products (biomass, biodiesel, oil, ...)

Energy equivalent of inputs (fuel, fertilizer, manpower, ...)

We considered lignocellulosic and oleaginous plants
Criteria definition - Environmental criteria

- Evaluate the environmental impact of energy crops;
- Biological Territorial Capacity, BTC (unit of measure: Mcal/m²/year);
- Defined for each landscape element;
- \( x_{\text{ENVIRONMENTAL}} = \text{BTC}_{\text{SCENARIO}} - \text{BTC}_{\text{REFERENCE}} \)

\[
\text{BTC}_{\text{mean}} = \frac{\left( \sum S_i \cdot \text{BTC}_i \right)}{S_{\text{domain}}}
\]

- \( \text{BTC}_{\text{mean}} \) increase
- \( \text{BTC}_{\text{mean}} \) decrease

- Environmental quality improvement
- Environmental quality degradation

Scenario definition – Reference scenario
Scenario definition - Energetic maximization scenario

- Based on energetic potential of energy crops
- Application in the aftercare phase
- Landfill top cover with low slope

- Dense and deep root system

assumption: additional 50 cm thickness in top cover

Miscanthus
Scenario definition - Leachate phytodepuration scenario

- Based on the possibility of leachate phytodepuration
- Application during the landfill operation phase
- 4 years of activity
- Landfill top cover with low slope

Phytodepuration basin

30 cm growing layer
50 cm drainage layer
1 m clay layer

Final top cover (D.Lgs 36/2003)

1 m natural layer
50 cm drainage layer
50 cm clay layer
50 cm LFG dr. layer
compensation layer

Oil crops


Scenario definition
- Leachate phytodepuration scenario

---

### Material and methods

**Duration of each phytodepuration field:**

- **(a)** 2 years
  - From the year 0 to 4
  - From the year 4 to 6
  - From the year 8 to 10
  - Aftercare: from the year 12 to 42

- **(b)** 4 years
  - From the year 0 to 10
  - From the year 10 to 14
  - Aftercare: from the year 14 to 44

- **(c)** 4 years
  - From the year 0 to 6
  - From the year 6 to 10
  - From the year 10 to 14
  - Aftercare: from the year 14 to 44

- **(d)** 2 years
  - From the year 0 to 4
  - From the year 4 to 6
  - From the year 8 to 10
  - Aftercare: from the year 10 to 40

- **(e)** 4 years
  - From the year 0 to 6
  - From the year 6 to 10
  - Aftercare: from the year 10 to 40

---

**Legend**
- Landfill sectors
- Landfill in operation
- Phytotreatment basin
- Closed sector
Scenario definition - Leachate phytodepuration scenario

Particular of the phytotreatment basin
Scenario definition - Environmental compensation scenario

- based on the introduction of environmental compensation measures

Poplar
- around the landfill body
- energy crops with Medium Rotation Forestry (MRF) cutting cycle

Shrubs
- over the landfill top cover
- recreational area spaces and walking paths
**Scenario definition - Combination scenario**

- Combine the solutions adopted for the other scenarios
- Effects both in operation and aftercare phase
Multi-Criteria Analysis

- $x_i$ defined for each criteria
- Interval linearization:

\[
\frac{x_i - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}
\]

$x_{\text{min}}$ and $x_{\text{max}}$ are represent the minimum and the maximum $x_i$ between the scenarios

- Final scoring:

\[
\text{Best scenario} = \text{Max } \sum_i x_i w_i
\]

- Assumption: equal weighting of the criteria
## Economic criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environmental compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOTAL COST</strong></td>
<td>68,833,045.81</td>
<td>69,279,106.78</td>
<td>68,952,498.16</td>
<td>69,139,071.58</td>
<td>69,189,190.40</td>
</tr>
<tr>
<td></td>
<td>+446,060.98</td>
<td>+119,452.35</td>
<td>+306,025.78</td>
<td>+356,144.59</td>
<td></td>
</tr>
<tr>
<td><strong>TOP COVER</strong></td>
<td>4,671,169.43</td>
<td>4,903,115.54</td>
<td>4,697,521.94</td>
<td>4,671,169.43</td>
<td>4,872,542.55</td>
</tr>
<tr>
<td><strong>FINAL WORKS</strong></td>
<td>80,870.77</td>
<td>159,198.59</td>
<td>160,005.07</td>
<td>213,760.77</td>
<td>258,611.59</td>
</tr>
<tr>
<td><strong>LEACHATE MANAG. IN OPERATION</strong></td>
<td>1,917,973.00</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
</tr>
<tr>
<td><strong>LEACHATE MANAG. IN AFTERCARE</strong></td>
<td>3,068,401.95</td>
<td>2,957,635.58</td>
<td>3,067,199.32</td>
<td>3,068,401.95</td>
<td>2,839,732.21</td>
</tr>
<tr>
<td>X_{ECONOMIC}</td>
<td>0.00</td>
<td>-446,060.98</td>
<td>-119,452.35</td>
<td>-306,025.78</td>
<td>-356,144.59</td>
</tr>
</tbody>
</table>
## Economic criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environmental compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TOTAL COST</strong></td>
<td>68,833,045.81</td>
<td>69,279,106.78</td>
<td>68,952,498.16</td>
<td>69,139,071.58</td>
<td>69,189,190.40</td>
</tr>
<tr>
<td><strong>TOP COVER</strong></td>
<td>4,671,169.43</td>
<td>4,903,115.54</td>
<td>4,697,521.94</td>
<td>4,671,169.43</td>
<td>4,872,542.55</td>
</tr>
<tr>
<td><strong>FINAL WORKS</strong></td>
<td>80,870.77</td>
<td>159,198.59</td>
<td>160,005.07</td>
<td>213,760.77</td>
<td>258,611.59</td>
</tr>
<tr>
<td><strong>LEACHATE MANAG. IN OPERATION</strong></td>
<td>1,917,973.00</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
</tr>
<tr>
<td></td>
<td>0.00</td>
<td>-83,376.02</td>
<td>0.00</td>
<td>-83,376.02</td>
<td></td>
</tr>
<tr>
<td><strong>LEACHATE MANAG. IN AFTERCARE</strong></td>
<td>3,068,401.95</td>
<td>2,957,635.58</td>
<td>3,067,199.32</td>
<td>3,068,401.95</td>
<td>2,839,732.21</td>
</tr>
<tr>
<td></td>
<td>-446,060.98</td>
<td>-119,452.35</td>
<td>-306,025.78</td>
<td>-356,144.59</td>
<td></td>
</tr>
<tr>
<td>$x_{ECONOMIC}$</td>
<td>0.00</td>
<td>-446,060.98</td>
<td>-119,452.35</td>
<td>-306,025.78</td>
<td>-356,144.59</td>
</tr>
<tr>
<td>Economic criteria</td>
<td>Reference scenario</td>
<td>Energetic maximization scenario</td>
<td>Leachate phytodepuration scenario</td>
<td>Environmental compensation scenario</td>
<td>Combination scenario</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------</td>
<td>---------------------------------</td>
<td>-----------------------------------</td>
<td>-------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>TOTAL COST</td>
<td>68,833,045.81</td>
<td>69,279,106.78</td>
<td>68,952,498.16</td>
<td>69,139,071.58</td>
<td>69,189,190.40</td>
</tr>
<tr>
<td>TOP COVER</td>
<td>4,671,169.43</td>
<td>4,903,115.54</td>
<td>4,697,521.94</td>
<td>4,671,169.43</td>
<td>4,872,542.55</td>
</tr>
<tr>
<td>FINAL WORKS</td>
<td>80,870.77</td>
<td>159,198.59</td>
<td>160,005.07</td>
<td>213,760.77</td>
<td>258,611.59</td>
</tr>
<tr>
<td>LEACHATE MANAG. IN OPERATION</td>
<td>1,917,973.00</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
<td>1,917,973.00</td>
<td>1,834,596.98</td>
</tr>
<tr>
<td>LEACHATE MANAG. IN AFTERCARE</td>
<td>3,068,401.95</td>
<td>2,957,635.58</td>
<td>3,067,199.32</td>
<td>3,068,401.95</td>
<td>2,839,732.21</td>
</tr>
<tr>
<td></td>
<td>- 110,766.37</td>
<td>- 1,202.63</td>
<td>0.00</td>
<td>- 228,669.73</td>
<td></td>
</tr>
<tr>
<td>$X_{ECONOMIC}$</td>
<td>0.00</td>
<td>-446,060.98</td>
<td>-119,452.35</td>
<td>-306,025.78</td>
<td>-356,144.59</td>
</tr>
</tbody>
</table>
## Energetic criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environm. compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT (GJ)</strong></td>
<td>0</td>
<td>1199.94</td>
<td>107.35</td>
<td>737.68</td>
<td>2,044.97</td>
</tr>
<tr>
<td><strong>OUTPUT (GJ)</strong></td>
<td>0</td>
<td>24,877.99</td>
<td>101.86</td>
<td>11,414.73</td>
<td>36,394.57</td>
</tr>
<tr>
<td><strong>NET GAIN (GJ)</strong></td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
<tr>
<td>$X_{ENERGETIC} (GJ)$</td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
</tbody>
</table>
## Energetic criteria

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environm. compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT (GJ)</strong></td>
<td>0</td>
<td>1199.94</td>
<td>107.35</td>
<td>737.68</td>
<td>2,044.97</td>
</tr>
<tr>
<td><strong>OUTPUT (GJ)</strong></td>
<td>0</td>
<td>24,877.99</td>
<td>101.86</td>
<td>11,414.73</td>
<td>36,394.57</td>
</tr>
<tr>
<td><strong>NET GAIN (GJ)</strong></td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
<tr>
<td><strong>X\text{ENERGETIC} (GJ)</strong></td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
</tbody>
</table>
## Energetic criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environm. compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>INPUT (GJ)</strong></td>
<td>0</td>
<td>1199.94</td>
<td>107.35</td>
<td>737.68</td>
<td>2,044.97</td>
</tr>
<tr>
<td><strong>OUTPUT (GJ)</strong></td>
<td>0</td>
<td>24,877.99</td>
<td>101.86</td>
<td>11,414.73</td>
<td>36,394.57</td>
</tr>
<tr>
<td><strong>NET GAIN (GJ)</strong></td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
<tr>
<td>$X_{\text{ENERGETIC}}$</td>
<td>0</td>
<td>23,678.05</td>
<td>-5.49</td>
<td>10,782.06</td>
<td>34,454.62</td>
</tr>
</tbody>
</table>
Environmental criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environm. compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>t = 0 (Mcal/m²/year)</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>t &gt; 40 years</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>$x_{\text{ENVIRONMENTAL}}$ (Mcal/m²/year)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>0.16</td>
</tr>
</tbody>
</table>
## Environmental criteria

<table>
<thead>
<tr>
<th></th>
<th>Reference scenario</th>
<th>Energetic maximization scenario</th>
<th>Leachate phytodepuration scenario</th>
<th>Environm. compensation scenario</th>
<th>Combination scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>t = 0</strong></td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
</tr>
<tr>
<td>(Mcal/m²/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>t &gt; 40 years</strong></td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>1.06</td>
<td>1.06</td>
</tr>
<tr>
<td>(Mcal/m²/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x_{\text{ENVIRONMENTAL}} )</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>(Mcal/m²/year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The best scenario resulted the combination scenario;

The energetic and the environmental criteria are maximized by applying lignocellulosic crops;

All the scenarios showed an higher costs respect the reference case;

The costs for additional layers on the top cover are not amortized by savings in leachate management;

The phytodepuration scenario showed really promising economically. The current normative should integrate in a better way the application of new technologies.