Green Chemistry: 
Evaluation of Alternative Reaction Pathways 
Chapters 7 and 8 

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The selection of a reaction pathway is the key step to establish the environmental performance of a chemical process, affecting the downstream separation units and their energy requirements, emissions, and impacts.

1 Educational goals and topics covered in the module

1 Green Chemistry (Chapter 7) and

1 assessing potential environmental impacts based on limited information (Chapter 8)
### Educational goals and topics covered in the module

**Students will:**

1. understand a “Tier 1” approach for chemical process environmental evaluation
2. learn qualitative and quantitative approaches to Green Chemistry
3. be able to evaluate alternative reaction pathways; both economically and environmentally.

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**Education Goals and Topics Covered in the Module.** In addition, students should be thinking about environmental issues at each stage of the design process.
1. Guiding principles for Green Chemistry
   » Maximum incorporation of raw materials into final products
   » All chemicals should be nontoxic yet functional
   » Auxiliary substances (solvents) should be nontoxic
   » High energy efficiency
   » Use of renewable resources is recommended
   » Recyclable reagents and raw materials
   » End products should not persist in the environment
Feedstocks and solvents

1. **Important considerations**
   - **Human / ecosystem health properties**
     - Bioaccumulative?
     - Persistent?
     - Toxic?
     - Global warming, Ozone depletion, Smog formation?
     - Flammable or otherwise hazardous?
     - Renewable or non renewable resource?
   - **Life cycle environmental burdens?** - Ch 13, 14

**Feedstocks and Solvents.** Life cycle environmental burdens is a concept that as engineers we need to think about including the ultimate use and disposal of products.
## Synthesis Pathways

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Waste Generation Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Addition Reaction</strong></td>
<td>• completely incorporate starting material into product</td>
</tr>
<tr>
<td>Isobutylene + methanol → methyl tert-butyl ether</td>
<td></td>
</tr>
<tr>
<td>C₄H₈ + CH₃OH → (C₄H₉)-O-CH₃</td>
<td></td>
</tr>
<tr>
<td><strong>Substitution Reaction</strong></td>
<td>• stoichiometric amounts of waste are generated</td>
</tr>
<tr>
<td>Phenol + ammonia → analine + water</td>
<td></td>
</tr>
<tr>
<td>C₆H₅-OH + NH₃ → C₆H₅-NH₂ + H₂O</td>
<td></td>
</tr>
<tr>
<td><strong>Elimination Reaction</strong></td>
<td>• stoichiometric amounts of waste are generated</td>
</tr>
<tr>
<td>Ethylbenzene → styrene + hydrogen</td>
<td></td>
</tr>
<tr>
<td>C₆H₅-C₂H₅ → C₆H₅-C₂H₃ + H₂</td>
<td></td>
</tr>
</tbody>
</table>

Synthesis Pathways. Note: Different types of chemicals create different products and byproducts.
Atom and Mass Efficiency: Magnitude of Improvements Possible. Atom efficiency is a concept you see frequently in green chemistry, it is one way to look at efficiency but it is not the only way.

<table>
<thead>
<tr>
<th></th>
<th>Mass Efficiency (Basis 1 mole of product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆H₅-OH + NH₃ →</td>
<td>C₆H₅-NH₂ + H₂O</td>
</tr>
<tr>
<td></td>
<td>Mass in Product = (6 C)(12) + (7 H)(1) +</td>
</tr>
<tr>
<td></td>
<td>(0 O)(16) + (1 N)(14) = 93 grams</td>
</tr>
<tr>
<td></td>
<td>Mass in Reactants = (6 C)(12) + (9 H)(1) +</td>
</tr>
<tr>
<td></td>
<td>(1 O)(16) + (1 N)(14) = 111 grams</td>
</tr>
<tr>
<td></td>
<td>Mass Efficiency = 93/111 x 100 = 83.8%</td>
</tr>
</tbody>
</table>
Chapter 7: Adipic Acid Synthesis
Traditional vs. New

Traditional Route - from cyclohexanol/cyclohexanone

\[
\text{C}_6\text{H}_{12}\text{O} + 2 \text{HNO}_3 + 2 \text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{10}\text{O}_4 + \text{(NO, NO}_2, \text{N}_2\text{O, N}_2) \]

Cu (.1-.5%)  
V (.02-.1%)

92-96% Yield of Adipic Acid

- Carbon - 100%
- Oxygen - 4/9 x 100 = 44.4%
- Hydrogen - 10/18 x 100 = 55.6%
- Nitrogen - 0%

Product Mass = (6 C)(12) + (10 H)(1) + (4 O)(16) = 146 g

Reactant Mass = (6 C)(12) + (18 H)(1) + (9 O)(16) + (2 N)(14) = 262 g

Mass Efficiency = 146/262 x 100 = 55.7%

Davis and Kemp, 1991, Adipic Acid, in Kirk-Othmer Encyclopedia of Chemical Technology, V. 1, 466 - 493

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New Route - from cyclohexene

\[
\text{C}_6\text{H}_{10} + 4 \text{H}_2\text{O}_2 \xrightarrow{\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O} (1\%)} [\text{CH}_3(\text{n-C}_8\text{H}_{17})_3\text{N}]\text{HSO}_4 (1\%) \rightarrow \text{C}_6\text{H}_{10}\text{O}_4 + 4 \text{H}_2\text{O}
\]

90% Yield of Adipic Acid

- Carbon - 100%
- Oxygen - 4/8 x 100 = 50%
- Hydrogen - 10/18 x 100 = 55.6%

Product Mass = (6 C)(12) + (10 H)(1) + (4 O)(16) = 146 g
Reactant Mass = (6 C)(12) + (18 H)(1) + (8 O)(16) = 218 g

Mass Efficiency = 146/218 x 100 = 67%

Maleic anhydride (MA) synthesis: benzene vs butane - mass efficiency

**Benzene Route** *(Hedley et al. 1975, reference in ch. 8)*

\[
2 \text{C}_6\text{H}_6 + 9 \text{O}_2 \xrightarrow{\text{V}_2\text{O}_5, \text{MoO}_3} 2 \text{C}_4\text{H}_2\text{O}_3 + \text{H}_2\text{O} + 4 \text{CO}_2
\]

70% Yield of Maleic Anhydride from Benzene in Fixed Bed Reactor

\[
\text{Mass Efficiency} = \frac{2(4)(12) + 3(2)(16) + 2(2)(1)}{2(6)(12) + 9(2)(16) + 2(6)(1)} \times 100 = 44.4\%
\]

**Butane Route**

\[
\text{C}_4\text{H}_{10} + 3.5 \text{O}_2 \xrightarrow{(\text{VO})_2\text{P}_2\text{O}_5, \text{(air)}} \text{C}_4\text{H}_2\text{O}_3 + 4 \text{H}_2\text{O}
\]

60% Yield of Maleic Anhydride from Butane in Fixed Bed Reactor

\[
\text{Mass Efficiency} = \frac{(4)(12) + (3)(16) + (2)(1)}{(4)(12) + 3.5(2)(16) + (10)(1)} \times 100 = 57.6\%
\]


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Maleic Anhydride Synthesis Benzene vs. Butane – Mass Efficiency. Mass Efficiency is a green chemistry concept; you can also calculate atomic efficiency. There is no single “correct” measurement of efficiency.
Maleic anhydride (MA) synthesis: benzene vs butane - summary table

<table>
<thead>
<tr>
<th>Material</th>
<th>Stoichiometry</th>
<th>$/lb $</th>
<th>TLV (d)</th>
<th>TW (d)</th>
<th>Persistence (d)</th>
<th>log BCF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benzene Process</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene [71-43-2]</td>
<td>-1.19</td>
<td>0.184</td>
<td>10</td>
<td>100</td>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>Maleic Anhydride</td>
<td>1.00</td>
<td>0.530</td>
<td>0.25</td>
<td>---</td>
<td>1.7</td>
<td>7x10⁴</td>
</tr>
<tr>
<td><strong>Butane Process</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Butane [106-97-8]</td>
<td>-1.22</td>
<td>0.141</td>
<td>800</td>
<td>---</td>
<td>7.25</td>
<td>----</td>
</tr>
<tr>
<td>Maleic Anhydride</td>
<td>1.00</td>
<td>0.530</td>
<td>0.25</td>
<td>---</td>
<td>1.7</td>
<td>7x10⁴</td>
</tr>
</tbody>
</table>

2 Chemical Marketing Reporter (Benzene and MA 6/12/00); Texas Liquid (Butane 6/22/00)
5 ChemFate Database - www.esc.syres.com, EFDB menu item

Maleic Anhydride Synthesis: Benzene vs. Butane – Summary Table.
Think of the reaction pathways based on persistence, bioaccumulation, and toxicity (PBT). At this point the students have the group data necessary to calculate persistence and bioaccumulation, recommend providing data sources for toxicity.

Maleic Anhydride Synthesis:
Butane: 53% converted to MA and 30% Cox, 17% not converted
Main C4H10 +3.5O2 -> C4H2O3 + 4 H2O
Side C4H10 + 6.5 O2 -> 4 CO2 + 5 H2O
Side C4H10 + 4.5 O2 -> 4CO + 5 H2O

Benzene: 72% converted to MA and 26% converted to CO & CO2, 2% not converted
C6H6 + 4.5O2 -> C4H2O3 + 2H2O + 2CO2 +2H2O
Side C6H6 + 7.5O2 -> 6 CO2 + 3 H2O
Side C6H6 + 4.5O2 -> 6CO +3H2O
Maleic anhydride (MA) synthesis: benzene vs butane - tier 1 assessment

<table>
<thead>
<tr>
<th>Route</th>
<th>TLV Index Formula</th>
<th>TLV Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene Route</td>
<td>$\sum</td>
<td>\nu_i</td>
</tr>
<tr>
<td>Butane Route</td>
<td></td>
<td>$(1.22)(1/800) + (1.0)(1/0.25) = 4.00$</td>
</tr>
</tbody>
</table>

Where $\nu_i$ is the overall stoichiometric coefficient of reactant or product $i$.
Maleic anhydride (MA) synthesis: benzene vs butane - tier 1 assessment

EPA Index
Environmental Index (carcinogenic) = \( \sum_{i} n_{i} \times (\text{Maximum toxicity weight}) \)

**Benzene Route**
EPA Index = (1.19)(100) + (1.0)(0) = 119

**Butane Route**
EPA Index = (1.22)(0) + (1.0)(0) = 0

Maleic Anhydride Synthesis Benzene vs. Butane -- Tier 1 Assessment. None.
A More Detailed Analysis of MA Production

Shown are the major reactions for product and byproduct generation, with expected conversions, yields, and reaction conditions (temperature, pressure, etc.) for MA production from either benzene or n-butane. Most MA production has migrated from benzene to n-butane, and this represents one of the earliest examples of Green Chemistry making a significant change in chemical production.
Maleic anhydride (MA) production: Costs

**Level 1. Input / Output Information**

*Tier 1* Economic analysis (raw materials costs only)

**Benzene Process**

\[
\text{MA Yield} \times \text{Bz MW} \times \text{Benzene cost} = 0.0313 \text{ $/mole of MA}
\]

**n-Butane Process**

\[
\text{MA Yield} \times \text{nC4 MW} \times \text{nC4 cost} = 0.0203 \text{ $/mole of MA}
\]

*Assumption:* raw material costs dominate total cost of the process

Using this input / output information for the reaction step, we can compute raw material costs for each reaction route for MA production. n-butane is superior to benzene with regard to raw material costs, even when the benzene route exhibits higher conversions and yields compared to n-butane. One reason is because 2 of the carbons on the benzene molecule are not incorporated into the final product, MA.
A production rate of 1 mole of MA is chosen as the basis for this impact analysis. Shown also are estimated recoveries and pollution control efficiency for the chemicals in the process.
Maleic Anhydride Synthesis
Benzene vs Butane - Tier 1 Assessment

Benzene Exiting Reactor:
\[(1\text{ mole/}((0.70)(.99)) \times (1 - 0.95)) = 0.0722 \text{ mole benzene/mole of MA}\]

Benzene Emission from Pollution Control:
\[(0.01) \times (0.0722 \text{ mole/mole of MA}) = 7.22 \times 10^{-4} \text{ mole benzene/mole of MA}\]

n-Butane Exiting Reactor:
\[(1\text{ mole/}((0.60)(.99)) \times (1 - 0.85)) = 0.2525 \text{ mole n-butane/mole of MA}\]

n-Butane Emission from Pollution Control:
\[(0.01) \times (0.2525 \text{ mole/mole of MA}) = 2.53 \times 10^{-3} \text{ mole n-butane/mole of MA}\]
<table>
<thead>
<tr>
<th>Process</th>
<th>CO Exiting Reactor:</th>
<th>CO Emission from Pollution Control:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>( \frac{6}{2} = 1.082 ) mole CO/mole MA</td>
<td>( (0.01) \times (1.082 \text{ mole/mole of MA}) = 1.08 \times 10^{-2} ) mole CO/mole MA</td>
</tr>
<tr>
<td>n-Butane</td>
<td>( \frac{4}{2} = 0.842 ) mole CO/mole MA</td>
<td>( (0.01) \times (0.842 \text{ mole/mole of MA}) = 8.42 \times 10^{-3} ) mole CO/mole MA</td>
</tr>
</tbody>
</table>
### Chapter 8: Maleic Anhydride Synthesis

Benzene vs Butane - Tier 1 Assessment

<table>
<thead>
<tr>
<th>Process</th>
<th>CO₂ Exiting Reactor</th>
<th>CO₂ Emission from Pollution Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benzene</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MA mole</td>
<td>6</td>
<td>3.082 mole CO₂ per mole MA</td>
</tr>
<tr>
<td>CO mole</td>
<td>2.705 (0.99)(0.9)</td>
<td>0.99 (0.842) mole CO₂ per mole MA</td>
</tr>
<tr>
<td>Reactor Exiting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MA mole</td>
<td>4.622 (0.6) (0.99)</td>
<td>0.99 (3.082) mole CO₂ per mole MA</td>
</tr>
<tr>
<td>CO mole</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td><strong>n-Butane</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MA mole</td>
<td>6</td>
<td>2.705 mole CO₂ per mole MA</td>
</tr>
<tr>
<td>CO mole</td>
<td>2.705 (0.99)(0.9)</td>
<td>0.99 (0.842) mole CO₂ per mole MA</td>
</tr>
</tbody>
</table>

\[
\text{Mole} \text{ CO}_2 = \frac{2 \times \text{mole CO}_2}{\text{mole MA}} + \frac{\text{mole/((0.7)(.99))} \times (0.95 - 0.7) \times 6}{2} = \frac{3.082 \text{ mole CO}_2}{\text{mole MA}}
\]

\[
\text{Mole} \text{ CO}_2 = (3.082 + (0.99)(1.082) + (0.99)(0.0722)(6) + (0.01)(0.99)(4) = 4.622 \frac{\text{mole CO}_2}{\text{mole MA}}
\]

\[
\text{Mole} \text{ CO}_2 = \frac{4 \times \text{mole/((0.60)(.99))} \times (0.85 - 0.6)}{2} = \frac{0.842 \text{ mole CO}_2}{\text{mole MA}}
\]

\[
\text{Mole} \text{ CO}_2 = (0.842 + (0.99)(0.842) + (0.99)(0.25)(4) + (0.01)(0.99)(4) = 2.705 \frac{\text{mole CO}_2}{\text{mole MA}}
\]
This table summarizes the rates of reactants, products, and byproduct entering and leaving the reactor as well as the emission of pollutants from the pollution control equipment to the environment. These emission estimates are the basis for calculating environmental impact indicators.
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### Benzene process

<table>
<thead>
<tr>
<th></th>
<th>Benzene</th>
<th>CO</th>
<th>CO₂</th>
<th>Maleic anhydride</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor inlet</td>
<td>1.13E-01</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>1.13E-01</td>
</tr>
<tr>
<td>Reactor outlet</td>
<td>5.63E-03</td>
<td>3.03E-02</td>
<td>1.36E-01</td>
<td>9.90E-02</td>
<td>2.71E-01</td>
</tr>
<tr>
<td>Separation unit</td>
<td>5.63E-05</td>
<td>3.03E-04</td>
<td>2.03E-01</td>
<td>9.90E-06</td>
<td>2.03E-01</td>
</tr>
</tbody>
</table>

### n-Butane process

<table>
<thead>
<tr>
<th></th>
<th>n-Butane</th>
<th>CO</th>
<th>CO₂</th>
<th>Maleic anhydride</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor inlet</td>
<td>9.76E-02</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>0.00E+00</td>
<td>9.76E-02</td>
</tr>
<tr>
<td>Reactor outlet</td>
<td>1.46E-02</td>
<td>2.36E-02</td>
<td>3.71E-02</td>
<td>9.90E-02</td>
<td>1.74E-01</td>
</tr>
<tr>
<td>Separation unit</td>
<td>1.46E-04</td>
<td>2.36E-04</td>
<td>1.19E-01</td>
<td>9.90E-06</td>
<td>1.19E-01</td>
</tr>
</tbody>
</table>

This table summarizes the rates of reactants, products, and byproduct entering and leaving the reactor as well as the emission of pollutants from the pollution control equipment to the environment. These emission estimates are the basis for calculating environmental impact indicators.
### Average Emission Factors for Chemical Process Units

Calculated from the US EPA L&E Database

<table>
<thead>
<tr>
<th>Process Unit</th>
<th>$EF_{av}$ (kg emitted/10^3 kg throughput)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Vents</td>
<td>1.50</td>
</tr>
<tr>
<td>Distillation Columns Vents</td>
<td>0.70</td>
</tr>
<tr>
<td>Absorber Units</td>
<td>2.20</td>
</tr>
<tr>
<td>Stripping Columns</td>
<td>0.20</td>
</tr>
<tr>
<td>Sumps/Decanters</td>
<td>0.02</td>
</tr>
<tr>
<td>Dryers</td>
<td>0.70</td>
</tr>
<tr>
<td>Cooling Towers</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Now that we have estimated direct emissions from the stream exiting the process, we can estimate emissions of chemicals from major pieces of equipment. For this we use the equipment input/out mass flow rates, concentrations, and emission factors from the US EPA. These emission factors were obtained by averaging the factors over a number of case studies involving a number of process flowsheets.
The SCENE software is used to estimate emissions from process equipment using emission factors listed previously, it calculates environmental fate using a "Level I" multimedia compartment model (partitioning among air, water, soil, and sediment), and calculates nine impact indices, similar to those listed in the previous slides. We will calculate environmental indices using the emissions estimated for the MA process in the previous table.
1. Open SCENE and then open the EFRAT main window (Figure 2-13 of Tutorial).
2. Add chemicals: benzene, CO, CO₂ and maleic anhydride.
   - Open ‘PFD’ menu, select ‘chemical list’ and then open the following window (Figure 3-2 of Tutorial).

   This window contains a list of ‘Chemicals in Database’. You can choose chemicals from this list and import them to the list of ‘Chemicals in Current PFD’.
   - Find chemical benzene. Use the vertical scroll bar of the chemical list to move down the list until benzene becomes visible, then highlight it.
   - Import chemical benzene. Click ‘Import This Chemical’ button. Benzene will appear in the list of ‘Chemicals in Current PFD’ (Figure 3-3 of Tutorial).

   On the right side of this window, it displays two pages of ‘Properties of Selected Chemical (Benzene)’. If there are some data unavailable for one chemical, the data cell will display ‘Unavailable’ and will be highlighted.
2. Add chemicals: benzene, CO, CO₂ and maleic anhydride.

- Open ‘PFD’ menu, select ‘chemical list’ and then open the following window (Figure 3-2).

  This window contains a list of ‘Chemicals in Database’. You can choose chemicals from this list and import them to the list of ‘Chemicals in Current PFD’.

- Find chemical benzene. Use the vertical scroll bar of the chemical list to move down the list until benzene becomes visible, then highlight it.

- Import chemical benzene. Click ‘Import This Chemical’ button. Benzene will appear in the list of ‘Chemicals in Current PFD’ (Figure 3-3).

On the right side of this window, it displays two pages of ‘Properties of Selected Chemical (Benzene)’. If there are some data unavailable for one chemical, the data cell will display ‘Unavailable’ and will be highlighted.
EFRAT program: All chemicals added

- Import chemicals CO, CO₂, and maleic anhydride following the same procedures as benzene (Figure 3-4 of Tutorial).
- Click ‘OK’, exit this window and return to the EFRAT main window, or click ‘Cancel’ to abandon these changes.
3. Add reactor emission.
   - Open ‘PFD’ menu, select ‘Emissions’ and then click ‘Add New Emission…’. You can choose to add emissions from eight different sources (Figure 3-5 of Tutorial).
   - Select ‘Reactor’, then click ‘OK’ and enter into the reactor emissions window (Figure 3-6). EFRAT gives this emission a default name, ‘Reactor 1’. You can rename it by activating ‘Item Name’ field and inputting a new name.
   - Input total feed flow rate and total product flow rate from Table 3-2. Please note that the unit of the flow rate in this evaluation is kg/mole of MA. However, in EFRAT, this unit does not exist. We can use the unit of flow rate as ‘kg/yr’ and then substitute it with ‘kg/mole of MA’ in the final results.
3. Add reactor emission.
   - Select ‘Reactor’, then click ‘OK’ and enter into the reactor emissions window (Figure 3-6 of Tutorial). EFRAT gives this emission a default name, ‘Reactor 1’. You can rename it by activating ‘Item Name’ field and inputting a new name.
   - Input total feed flow rate and total product flow rate from Table 3-2 of Tutorial. Please note that the unit of the flow rate in this evaluation is kg/mole of MA. However, in EFRAT, this unit does not exist. We can use the unit of flow rate as ‘kg/yr’ and then substitute it with ‘kg/mole of MA’ in the final results.
   - Input mass fraction of each chemical in both feed and product streams. These can be calculated from Table 3-2 by dividing the flow rate of one chemical by the total flow rate.
   - Click ‘OK’ to save the changes and return to the EFRAT main window, or click ‘Cancel’ to abandon these changes.
4. Add direct emission.
   - Open ‘PFD’ menu, select ‘Emissions’ and then click ‘Add New Emission…’ (Figure 3-5 of Tutorial).
   - Select ‘Direct’, then click ‘OK’ and enter into the direct emissions window (Figure 3-7 of Tutorial).
   - Input total flow rate and mass fraction of each chemical, calculated from Table 3-2 of Tutorial.
   - Click ‘OK’ to save the changes and return to the EFRAT main window, or click ‘Cancel’ to abandon these changes.
Now the EFRAT main window shows two emissions (Figure 3-8 of Tutorial).
EFRAT program: Emissions Window
5. View the results.
Open menu ‘PFD’ and select ‘Emission Summary…’ to view the results.

This table can be pasted into MS Excel by clicking ‘Edit’ menu and then selecting its submenu.
- Click ‘Close’ and return to the EFRAT main window.
Recap

Green Chemistry concepts and Atom Economy are useful for designing more environmentally beneficial reaction pathways. Early design Green Engineering analysis methods for environmental impacts of alternatives.

1. Educational goals and topics covered in the module
2. Green Chemistry (Chapter 7) and assessing potential impacts based on limited information (Chapter 8)