Easy LCCP analysis for Domestic Hot Water Heat Pumps

Pavel Makhnatch
KTH Royal Institute of Technology, Sweden


27 August 2019
Why performing an LCCP analysis?
Total emissions of cooling sector

Source: https://www.green-cooling-initiative.org/country-data/#!total-emissions/all-sectors/absolute
Incentives to reduce direct and indirect climate impact:

Globally:
The Paris Agreement
...aims to strengthen the global response to the threat of climate change by “holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels...

Locally:
- EU: F-gas Regulation

**Article 11 exemption from equipment POM:**
The prohibition ... shall not apply to equipment for which ... due to higher energy efficiency during its operation, its lifecycle CO₂ equivalent emissions would be lower than those of equivalent equipment which ...does not contain hydrofluorocarbons.

- Future legislations and policies
Metrics for climate change impact assessment

• GWP (global warming potential)
• GTP (global temperature change potential)
• Other (GCP, GDP, etc.)

• TEWI (total equivalent warming impact)
• LCCP (life cycle climate potential)
• Other (EIF, etc.)
Performing LCCP analysis isn’t difficult, is it?
Guideline for Life Cycle Climate Performance

January 2016

V. 1.2
LCCP = Direct Emissions + Indirect Emissions

Direct Emissions = C * (L * ALR + EOL) * (GWP + Adp. GWP)

Indirect Emissions = L * AEC * EM + ∑(m * MM) + ∑(mr * RM) + C * (1+ L * ALR) * RFM + C * (1-EOL) * RFD

C = Refrigerant Charge (kg)
L = Average Lifetime of Equipment (yr)
ALR = Annual Leakage Rate (% of Refrigerant Charge)
EOL = End of Life Refrigerant Leakage (% of Refrigerant Charge)
GWP = Global Warming Potential (kg CO₂/kg)
Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO₂/kg)
AEC = Annual Energy Consumption (kWh)
EM = CO₂ Produced/kWh (kg CO₂/kWh)
m = Mass of Unit (kg)
MM = CO₂ Produced/Material (kg CO₂/kg)
Mr = Mass of Recycled Material (kg)
RM = CO₂ Produced/Recycled Material (kg CO₂/kg)
RFM = Refrigerant Manufacturing Emissions (kg CO₂/kg)
RFD = Refrigerant Disposal Emissions (kg CO₂/kg)
Example of LCCP calculation:

\[
\text{LCCP} = \text{Direct Emissions} + \text{Indirect Emissions}
\]

\[
\text{Direct Emissions} = C \times (L \times \text{ALR} + \text{EOL}) \times (\text{GWP} + \text{Adp. GWP})
\]

\[
\text{Indirect Emissions} = L \times \text{AEC} \times \text{EM} + \sum (m \times \text{MM}) + \sum (m_r \times \text{RM}) + C \times (1 + L \times \text{ALR}) \times \text{RFM} + C \times (1-\text{EOL}) \times \text{RFD}
\]

- **C** is the refrigerant charge, 1 L
- **L** is the average lifetime of equipment, 15 yr
- **ALR** is the annual leakage rate, 2.5%
- **EM**, kg CO₂ produced/kWh, 0.03 kgCO₂e kWh⁻¹
- **GWP** is the Global Warming Potential, in kg CO₂e·kg⁻¹

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R290</th>
<th>R1234yf</th>
<th>R152a</th>
<th>R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 yr</td>
<td>3.3</td>
<td>0.4</td>
<td>137.4</td>
<td>1297.7</td>
</tr>
<tr>
<td>AEC, kWh yr⁻¹</td>
<td>18 323</td>
<td>17 360</td>
<td>18 698</td>
<td>17 999</td>
</tr>
<tr>
<td>RFM, kgCO₂e/kg ref.</td>
<td>0.05</td>
<td>7.5</td>
<td>13.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

- Unit mass (100 kg); composition, material manufacturing and recycling emissions, – according to IIR LCCP guideline
- Adp. GWP and RFD – neglected
LCCP analysis results:

<table>
<thead>
<tr>
<th></th>
<th>Indirect</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>R290</td>
<td>BETTER</td>
<td></td>
</tr>
<tr>
<td>R152a</td>
<td>BEST</td>
<td></td>
</tr>
<tr>
<td>R1234yf</td>
<td>BETTER</td>
<td></td>
</tr>
<tr>
<td>R134a</td>
<td>WORST</td>
<td></td>
</tr>
</tbody>
</table>

kg CO₂e
- Was it difficult?

- Not

(provided that all the input values are available and certain)

But is it always the case?
Average lifetime of equipment

Assumed 15 yr.

Source: Hiller 2000, ASHRAE Journal

Average or median?
Carbon intensity of el. generation (EM) assumptions:

- EM assumed for a country average at production
- Regional average vs. country average?
- Regional average vs. global average?
- Country average vs. zone average?
- EM of generated energy or EM of used energy?
- EM of used energy today, or considering future energy mix?
Carbon intensity of el. generation assumptions:


DOI 10.1016/j.trd.2017.07.012
Table 3.1: GWP and Adaptive GWP

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>GWP (kg CO&lt;sub&gt;2e&lt;/sub&gt;/kg)</th>
<th>Adaptive GWP (kg CO&lt;sub&gt;2e&lt;/sub&gt;/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HFC-32</td>
<td>677</td>
<td>Not available</td>
</tr>
<tr>
<td>HFO-1234yf</td>
<td>&lt; 1</td>
<td>3.3 [6, 19, 41]</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>1300</td>
<td>1.6 [6, 19, 41]</td>
</tr>
<tr>
<td>HC-290</td>
<td>3</td>
<td>Not available</td>
</tr>
<tr>
<td>HFC-404A</td>
<td>3,943</td>
<td>Not available</td>
</tr>
<tr>
<td>HFC-410A</td>
<td>1,924</td>
<td>Not available</td>
</tr>
</tbody>
</table>

Table 4.4: Refrigerant Manufacturing Emissions

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Manufacturing Emissions (kg CO&lt;sub&gt;2e&lt;/sub&gt;/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFC-32</td>
<td>7.2</td>
</tr>
<tr>
<td>HFO-1234yf</td>
<td>13.7</td>
</tr>
<tr>
<td>HFC-134a</td>
<td>5.0</td>
</tr>
<tr>
<td>HC-290</td>
<td>0.05</td>
</tr>
<tr>
<td>HFC-404A</td>
<td>16.7</td>
</tr>
<tr>
<td>HFC-410A</td>
<td>10.7</td>
</tr>
</tbody>
</table>
Typical problems in published LCCP studies:

- C, m: not modified between different refrigerants and/or configurations
- ALR: often independent on refrigerant and the effect of leakage on COP are not reflected
- L: old or arbitrary chosen values
- EOL: often not justified
- AEC: has significant impact on LCCP, but the uncertainty of theoretical analysis (or measured data) is not addressed
- EM: very different values can be assumed from study to study
- MM, RM, RFM: data source? What about the values after 15yr?
Methods for dealing with uncertainties

- **Scientific**: Performing more research in order to increase the quality of the input values.
- **Constructivist**: Involving stakeholders so as to create consensus, standard and, or ‘good practice’.
- **Legal**: Relying on legal authorities and their decrees.
- **Statistical**: Integrating statistical methods to evaluate uncertainties.
Some of the inputs, mean value and deviation from the mean:

- C is the refrigerant charge, $1\pm0.1$ L
- L is the average lifetime of equipment, $15\pm1$ yr
- ALR is the annual leakage rate, $2.5\%\pm0.125\%$
- EM, kg CO$_2$ produced/kWh, $0.03\pm5\%$ kgCO$_2$e kWh$^{-1}$
- GWP is the Global Warming Potential, in kg CO$_2$e·kg$^{-1}$; Adp. GWP – neglected

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>R290</th>
<th>R1234yf</th>
<th>R152a</th>
<th>R134a</th>
</tr>
</thead>
<tbody>
<tr>
<td>GWP 100 yr</td>
<td>$3.3\pm1.65$</td>
<td>$0.4\pm0.2$</td>
<td>$137.4\pm55$</td>
<td>$1297.7\pm433$</td>
</tr>
<tr>
<td>AEC, kWh yr$^{-1}$</td>
<td>$18\ 323\pm10%$</td>
<td>$17\ 360\pm10%$</td>
<td>$18\ 698\pm10%$</td>
<td>$17\ 999\pm10%$</td>
</tr>
<tr>
<td>RFM, kgCO$<em>2$e/kg$</em>{ref.}$</td>
<td>$0.05\pm10%$</td>
<td>$7.5\pm10%$</td>
<td>$13.7\pm10%$</td>
<td>$5.0\pm10%$</td>
</tr>
</tbody>
</table>

- Unit mass ($100$ kg$\pm10\%$); composition, material manufacturing emissions and recycling emissions, – according to IIR guidelines
Propagated uncertainty of LCCP

<table>
<thead>
<tr>
<th>Compound</th>
<th>Indirect</th>
<th>Direct</th>
</tr>
</thead>
<tbody>
<tr>
<td>R290</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R152a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1234yf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R134a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R290</td>
<td>R152a</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------</td>
<td>---------------</td>
</tr>
<tr>
<td>LCCP, kg CO₂e</td>
<td>8483.6 ± 704.3</td>
<td>8133.6 ± 669.9</td>
</tr>
<tr>
<td>Direct, kg CO₂e</td>
<td>1.0 ± 0.5</td>
<td>72.9 ± 30.4</td>
</tr>
<tr>
<td>Indirect, kg CO₂e</td>
<td>8483.6 ± 704.3</td>
<td>8060.7 ± 669.2</td>
</tr>
<tr>
<td>- energy use</td>
<td>8245.4 ± 687.1</td>
<td>7812.0 ± 651.0</td>
</tr>
<tr>
<td>- material</td>
<td>232.6 ± 16.5</td>
<td>232.6 ± 16.5</td>
</tr>
<tr>
<td>manufacture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- material</td>
<td>5.6 ± 0.6</td>
<td>5.6 ± 0.6</td>
</tr>
<tr>
<td>recycling</td>
<td>0.0 ± 0.0</td>
<td>10.4 ± 1.1</td>
</tr>
<tr>
<td>- refrigearnt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>manufacturing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Indirect (energy use): L[yr] * AEC[kWh] * EM[kgCO₂/kWh]
Approach for easier LCCP:

1. Identify initial set of the input values and their deviation from the mean
2. Perform LCCP and calculate uncertainty of LCCP (e.g. using Monte Carlo)
3. Reduce uncertainty of LCCP by improving input values. When not possible, consider performing several LCCP with different inputs (sensitivity analysis)
4. Reiterate until the result is achieved or no further improvement possible
LCCP calculation using Monte-Carlo. Example

The following terms have been used to indicate the assessed likelihood of an outcome or a result:

- virtually certain - 99–100% probability
- very likely - 90–100%,
- likely - 66–100%,
- about as likely as not - 33–66%,
- unlikely - 0–33%,
- very unlikely - 0–10%,
- exceptionally unlikely - 0–1%
Conclusions:

• There is a need for environmental metric that combines direct and indirect emissions and can be reliably incorporated in future legislations
• LCCP can be used as such metric if the uncertainties and variation of input values is addressed
• Iterative approach of refining LCCP input data can facilitate the comparative LCCP analysis
• In some cases, when the data quality can not be obtained, the LCCP analysis can not lead to definitive conclusions
Questions?

Pavel Makhnatch
linkedin.com/in/pavelma