CO_2

BioLPG's carbon savings

in Ireland

In heating, haulage and forklifts

Atlantic Consulting

April 2018

BioLPG carbon-footprint comparisons

TABLES

FIGURES

1 BioLPG offers lower-carbon heating, haulage and forklifts in Ireland

Atlantic Consulting has compared the carbon footprint of BioLPG against competing fuels/energies in heating, haulage and powering forklifts in the Republic of Ireland. BioLPG in most cases can offer significant reductions in carbon emissions.

1.1 WTW and LHV – a note about terminology

This comparison has been conducted over the full life-cycle of BioLPG and its competing fuels. A full life-cycle covers all activities around a fuel, starting with its emergence from the environment through its return to the environment, i.e. the 'cradle-to-grave' life of the fuel. Often this scope is referred to as 'Well-to-Wheel', WTW, i.e. meaning from the wellhead of petroleum production to the wheel of an automobile – or the equivalent for non-fossil fuels or non-automotive applications. WTW is often broken into two subparts: Well-to-Tank, or WTT (supply of the fuel), and Tank-to-Wheel, or TTW (combustion of the fuel).

With one exception, the following comparison is based on lower heating values (LHV, sometimes also called 'net heating value' or 'net calorific value' NCV). Lower heating value is the heat delivered by a fuel when combusted, without condensing the water in the combustion exhaust. In Europe, most fuels in Europe are sold on a LHV basis and most footprint comparisons are done on a LHV basis. Higher heating value is the heat delivered by a fuel when combusted, with condensation of the water in the combustion exhaust.

1.2 Heating

The heating comparison is broken into two parts. One is for home heating, based on a peer-reviewed, authoritative comparison that has been cited 10 times[1] (Johnson, 2012). This comparison considers he entire heating system and its efficiencies. The second comparison is for 'other heating', i.e. heating in general, based only on published emission factors and not entailing a detailed analysis of specific heating systems.

1.2.1 Home heating

In Ireland, according to the most authoritative available figures, substituting 100% BioLPG (Table 1, far-right column) for conventional fuels/energies reduces full life-cycle carbon emissions for five out of six competing fuels. Only in one case, wood pellets, would carbon emissions be increased by substituting BioLPG. In four cases – heating oil, electric resistance, coal and peat – substituting 100% fossil LPG would also reduce carbon emissions (Table 1, 2nd column). As the blend of BioLPG to fossil LPG increases (each successive column to the right in Table 1), reductions increase. In 29 of 36 cases shown (in green in Table 1), LPG-BioLPG reduces carbon emissions.

[1] see https://scholar.google.com/citations?view_op=view_citation&hl=en&user=J4rsUqMAAAAJ&citation_for_view=J4rsUqMAAAAJ:WF5omc3nYNoC

Table 1: Heating carbon-footprint reduction by substituting competing fuel with LPG/BioLPG, N Ireland[2]

Reduction versus	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil	15%	30%	38%	44%	58%	72%
Electric resistance	51%	59%	64%	68%	76%	84%
Coal	52%	60%	64%	68%	76%	84%
Peat	55%	62%	67%	70%	77%	85%
Wood	-279%	-216%	-178%	-153%	-90%	-27%
Natural gas	-6%	12%	22%	29%	47%	64%

1.2.2 Other heating

In Ireland, according to the most authoritative available figures, substituting 100% BioLPG (Table 2, far-right column) for conventional fuels/energies reduces full life-cycle carbon emissions for all six competing fuels. In three cases – gas oil, heavy heating oil and kerosene – substituting 100% fossil LPG would also reduce carbon emissions (Table 2, 2nd column). As the blend of BioLPG to fossil LPG increases (each successive column to the right in Table 2), reductions increase. In 24 of 30 cases shown (in green in Table 2), LPG-BioLPG reduces carbon emissions.

Table 2: Heating carbon-footprint reduction by substituting competing fuel with LPG/BioLPG, N Ireland[3]

Reduction versus	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Biodiesel	-270%	-199%	-157%	-128%	-57%	13%
Gas oil	19%	35%	44%	50%	66%	81%
Heating oil, heavy	21%	36%	45%	51%	66%	81%
Kerosene	17%	33%	42%	49%	64%	80%
LPG, fossil	0%	19%	31%	38%	57%	77%

1.3 Haulage

Calor foresees selling BioLPG into the haulage market as unblended, 100% BioLPG. At this mixture, BioLPG will incur a carbon footprint significantly below that of its competing mono-fuels and fuel mixtures. For marketing statements, we believe the following statements can be asserted:

- ***For heavy duty road vehicles powered by diesel, LNG or CNG, substituting BioLPG can reduce operating footprints by 70+%.***
- ***For heavy duty road vehicles powered by diesel-LPG or diesel-CNG blends, substituting BioLPG (for the LPG or CNG) can reduce operating footprints by around 20%.***

[2] Negative numbers mean that substitution with LPG/BioLPG increases carbon footprint
[3] Negative numbers mean that substitution with LPG/BioLPG increases carbon footprint

1.4 *Forklifts*

In Ireland, according to the most authoritative available figures, substituting 100% fossil LPG for diesel already reduces carbon emissions by 9%. This gap expands as BioLPG is added to the blend, rising to a 79% reduction for 100% BioLPG (Table 3). Against electricity (Table 3), the competition is tighter: only at a BioLPG blend of 50% and above does the substitution achieve lower carbon than electricity. In 9 of 12 cases shown (in green in Table 3), LPG-BioLPG reduces carbon emissions.

Table 3: Forklift carbon-footprint reduction by substituting competing fuel with LPG/BioLPG, N Ireland[4]

	LPG 100%	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Reduction, Diesel-LPG	9%	27%	37%	44%	61%	79%
Reduction, Electric-LPG	-50%	-21%	-4%	7%	36%	65%

1.5 *Organisation of this report*

After presenting the basis footprint data in the next two chapters, a following chapter presents more detail behind the results summarised above. A final chapter presents the references.

[4] Negative numbers mean that substitution with LPG/BioLPG increases carbon footprint

2 LPG footprints

This chapter presents the carbon footprints of BioLPG and conventional LPG. The next chapter presents those of the competing fuels/energies, which in the subsequent chapter are compared.

2.1 BioLPG's footprint

The first peer-reviewed carbon footprint of biopropane has been published recently (Johnson, 2017); this is the basis of the BioLPG footprint presented here. The 'field-to-tank' footprint is the entire footprint for BioLPG, i.e. the combustion footprint is by definition counted as zero, because the feedstock is renewable.

The key figure for BioLPG is its average consumer footprint, i.e. the footprint of the end-user. The 'base case' footprint in this comparison is 16.8 g CO_2 equivalent per MJ of BioLPG at lower heating value (Table 4). In other units, this is 782.0 g CO_2e/kg and 397.4 g CO_2e/l. This base case assumes that footprints throughout the BioLPG supply chain are allocated by *energy content*, which is the default method under the European Union's Renewable Energy Directive (European Commission, 2009).

Table 4: BioLPG's carbon footprint, economic and energy scenarios

		g CO_2e/MJ LHV feedstock		**g CO_2e/MJ LHV mix**	
		Allocation method		***Allocation method***	
RAW MATERIALS/INPUTS	**Wt % Feed**	*Economic*	*Energy*	*Economic*	*Energy*
Products					
Palm oil w/o methane capture	8%	16.2	39.4	1.3	3.1
Palm oil with methane capture	4%	10.8	26.2	0.5	1.1
Other veg oil	1%	19.4	47.4	0.2	0.5
PFAD w/o methane capture	6%	15.0	36.3	0.8	2.0
Residues/Wastes					
UCO	54%	5.2	11.1	2.8	6.0
Tallow	27%	5.2	11.1	1.4	3.0
TOTALS					
Weighted average composite				7.0	15.7
Storage & Distribution, UK[5]				1.1	1.1
Average consumer footprint					
g CO2e per MJ				8.1	16.8
g CO2e per kilogramme				375.7	782.0
g CO2e per litre				190.9	397.4

As an alternative, the footprint as allocated by *economic value* is also presented (Table 4), because this allocation method is favoured by many analysts and is often applied by the UK

[5] Taken from Calor's Carbon Count 2014, bulk LPG distribution

Government[6]. This is less than half of the footprint allocated by energy, 8.1 g CO_2e per MJ of BioLPG.

The average consumer footprint has been compiled from:

- Footprints published in (Johnson, 2017), which are presented in the columns (Table 4) under g CO_2e/MJ LHV ***feedstock***, i.e. the footprint for one MJ of BioLPG made from that raw material.
- An estimate of the percentage of each feedstock used to make BioLPG from 2017-2020, presented in the column ***Wt% Feed***. This is taken from the far-right-hand column of an analysis of feedstocks (Table 5).
- These two inputs have been multiplied to generate a weighted average presented in the columns (Table 4) headed with g CO_2e/MJ LHV ***mix***.

The feedstock analysis (Table 5) comes from two sources: (Neste Corporation, 2017) for the 2014-2016 actual figures, and for the projection (Delage et al., 2017). The latter is a submission to the French Government's agency for carbon footprints, Base Carbone. The Neste report covers only its own production. The Base Carbone estimate covers all expected production in Europe.

Table 5: Feedstock mix for BioLPG production in Europe, 2014-2020

	Neste report			Base Carbone estimate				
Feedstock mix	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**Avg 2017-20**
Palm oil				18%	15%	10%	5%	
of which								
Palm oil w/o methane capture				12%	10%	7%	3%	8%
Palm oil with methane capture				6%	5%	4%	2%	4%
Other veg oil				2%	1%	1%	0%	1%
UCO				52%	53%	55%	57%	54%
Tallow				23%	25%	29%	32%	27%
PFAD w/o methane capture				5%	5%	6%	6%	6%
Product, UK				25%	21%	17%	11%	19%
Waste/residue, UK				75%	78%	84%	89%	82%
Veg oil, any kind	38%	32%	22%					
Waste or residue	62%	68%	78%					

2.2 Conventional LPG's footprint

For the footprint of conventional LPG, in this study we have used official figures from the Irish Government and the European Union(Table 6). For LPG's physical properties, we also have used official Irish figures (Table 7). Values for LPG physical properties vary slightly

[6] However, for transport biofuels, the Government still applies energy allocation.

throughout the scientific and regulatory literature. This is partly due to the varying composition of LPG and probably also due to differences in test methods.

Table 6: LPG carbon footprints, Republic of Ireland

	g CO_2e per				
Life-cycle phase	**MJ LHV**	**MJ HHV**	**kg**	**litre**	**Data source**
Well-to-tank	8.0	7.5	379.1	198.0	EU Joint Research Centre, Institute for Energy and Transport
Tank-to-wheel (combustion)	63.7	59.3	3,003.8	1,568.6	(Sustainable Energy Authority of Ireland, 2018)
Well-to-wheel/stack	71.7	66.8	3,383.0	1,766.6	Sum of the above

Table 7: LPG physical properties (Sustainable Energy Authority of Ireland, 2018)

Property	Value	Unit
LPG heating value	47.16	MJ/kg lower heating value (LHV)
LPG heating value	50.75	MJ/kg higher heating value (HHV)
LPG density	522.19	kg/m3
LPG density	0.52219	kg/litre

3 Competing fuels' footprints

Here are the footprints – in g CO_2e/MJ of lower heating value – for fuels/energies that compete against BioLPG and LPG (Table 8). About half of them are official figures from the Irish Government, and these account for about 85% of the well-to-wheel (WTW) totals. Where no Irish figures were available, next-best authoritative sources were used. Lower heating value (LHV) footprints are presented, except for natural gas HHV, because the analysis has been done on an LHV basis. Higher heating value (HHV) footprints are used in some studies and references (often USA-based ones), so readers should always check this when making external comparisons.

Table 8: Competing fuel footprints, WTT and TTW, g CO_2e/MJ LHV

	WTT	Source	TTW	Source	WTW
Biodiesel	19.4	1	0.0	Assumed zero	19.4
CNG	11.4	1	56.8	2	68.2
Coal	14.8	1	94.6	7	109.4
Diesel	15.4	1	73.3	7	88.7
Electricity	17.1	3	133.7	7	150.8
Gas oil	15.4	1	73.3	7	88.7
Heating oil, light	14.6	1	73.3	7	87.9
Heating oil, heavy	14.6	1	76.0	7	90.6
Kerosene	14.6	1	71.4	7	86.0
LNG	21.1	1	56.5	5	77.6
LPG, fossil	8.0	4	63.7	7	71.7
LPG, bio	16.8	6	0.0	Assumed zero	16.8
Natural gas LHV	7.7	1	56.9	7	64.6
Natural gas HHV	6.9	Inferred from 1	51.2	Inferred from 7	58.1
Peat, briquettes	11.4	This study	98.9	7	110.3
Peat, milled	11.4	This study	116.7	7	128.1
Peat, sod	11.4	This study	104.0	7	115.4
Wood, logs	3.6	2	0.0	Assumed zero	3.6
Wood, pellets	3.6	2	0.0	Assumed zero	3.6

Key to Data Sources

Number	*Reference*
1	(UK Dept of Business Energy & Industrial Strategy, 2016)
2	(UK Dept of Business Energy & Industrial Strategy and UK DEFRA (predecessor), 2018)
3	(ecoinvent, 2016)
4	EU Joint Research Centre, Institute for Energy and Transport
5	(Johnson, 2018)
6	(Johnson, 2017)
7	(Sustainable Energy Authority of Ireland, 2018)

Both megajoules and kilowatthours are used as energy units in footprint comparisons. For ease of reference, the same footprints are also presented per kWh (Table 9).

Table 9: Competing fuel footprints, WTT and TTW, g CO_2e/kWh LHV

	WTT	TTW	WTW
Biodiesel	69.8	0	19.4
CNG	40.9	204.6	245.6
Coal	53.1	340.6	393.7
Diesel	55.3	263.9	319.1
Electricity	61.6	481.3	542.9
Gas oil	55.3	263.9	319.1
Heating oil, light	52.4	263.9	316.3
Heating oil, heavy	52.4	273.6	326.0
Kerosene	52.4	257.0	309.4
LNG	75.8	203.5	279.3
LPG, fossil	28.9	229.3	258.3
LPG, bio	60.4	0.0	60.4
Natural gas LHV	27.8	204.8	232.6
Natural gas HHV	25.0	184.2	209.1
Peat, briquettes	40.9	356.0	396.9
Peat, milled	40.9	420.1	461.0
Peat, sod	40.9	374.4	415.3
Wood, logs	13.1	0.0	13.1
Wood, pellets	13.1	0.0	13.1

The Irish Government publishes combustion (TTW) footprints for three types of peat: briquette, milled and sod (Sustainable Energy Authority of Ireland, 2018). However, it does not publish a well-to-tank footprint for peat, and inquiries to the Government and to an Irish academic who has published research on peat did not yield a figure.

So, Atlantic Consulting estimated its own figure: we took an average of the two published studies (Väisänen, 2014) (Kirkinen et al., 2007) that cover peat-for-fuel production[7]. Both studies are of production in Finland. Given the overall results for peat in comparison to BioLPG, use of the Finnish footprints is valid, because 1) they are relatively insignificant anyway, i.e. they are overpowered by the TTW footprints, and 2) the Finnish footprints are the next-best available ones, and from authoritative studies. Nonetheless, in future it would be better to use Irish footprints, if they can be determined.

[7] There are other studies that cover footprints of production of peat as an (agricultural) growing medium. Although the production of peat for fuel and agricultural medium appear to be similar, they report in different units for which conversion factors are very uncertain.

4 Footprint comparison details

Using the unitary footprints presented in the preceding two chapters together with fuel economy factors, the footprints by fuel are compared in this chapter. Three applications are considered:

- home heating;
- other heating
- haulage and
- forklift operation.

For each fuel in each application, we have compared it to:

- 100% LPG
- 25%/75% BioLPG/LPG
- 40%/60% BioLPG/LPG
- 50%/50% BioLPG/LPG
- 75%/25% BioLPG/LPG
- 100% BioLPG

The mixtures and equivalence of LPG and BioLPG are on the basis of energy content, i.e. the heating value of the fuels, which are assumed to be effectively equal[8]. In practical terms – heating value, density, Wobbe Index and the like – LPG and BioLPG are assumed to be identical.

How robust are these comparisons? Extensive experience in this sort of work suggests that footprint differences of 10% or less are possibly insignificant – they may well be within the margin of error. Those of 15% or more are usually significant, and defensible in a regulatory or commercial context.

4.1 Heating

The heating comparison is broken into two parts. One is for home heating, based on a peer-reviewed, authoritative comparison that has been cited 10 times[9] (Johnson, 2012). This comparison considers he entire heating system and its efficiencies. The second comparison is for 'other heating', i.e. heating in general, based only on published emission factors and not entailing a detailed analysis of specific heating systems.

4.1.1 Home heating

Calor foresees selling BioLPG into the home heating market as a mixture of LPG/BioLPG. At all mixtures evaluated, the bio-blend will incur a lower carbon footprint than its competitors, except for wood (Table 10).

[8] We say, 'effectively equal', because the actual values applied are different by about 0.5%. In real-life, heating values vary more than this, and such differences get lost in the rounding error, so they are effectively equal.
[9] see https://scholar.google.com/citations?view_op=view_citation&hl=en&user=J4rsUqMAAAAJ&citation_for_view=J4rsUqMAAAAJ:WF5omc3nYNoC

Table 10: Home heating footprints – competing fuels versus LPG/BioLPG

	% reduction in GHGs (CO2e/eq function)					
Reduction versus	***LPG 100%***	***BioLPG 25%***	***BioLPG 40%***	***BioLPG 50%***	***BioLPG 75%***	***BioLPG 100%***
Heating oil	15%	30%	38%	44%	58%	72%
Electric resistance	51%	59%	64%	68%	76%	84%
Coal	52%	60%	64%	68%	76%	84%
Peat	55%	62%	67%	70%	77%	85%
Wood	-279%	-216%	-178%	-153%	-90%	-27%
Natural gas	-6%	12%	22%	29%	47%	64%

The basis of all the home heating comparisons is (Johnson, 2012). We believe this is the most comprehensive dataset available in this area. It is also most authoritative, having been peer-reviewed and cited 10 times[10] in the scientific literature. The study estimated the carbon footprint of home heating/hot water systems over the lifetime of a typical boiler in Ireland (and several other European countries). It includes the footprints of not just the fuels from well-to-wheel, but also the manufacturing and disposing of the boiler hardware and the efficiencies of the heating systems.

4.1.1.1 Heating Oil

The detail behind the reduction is presented below (Table 11). It starts with the footprints of the heating-oil and the LPG systems. These are then split into two parts: a 'non-direct fuel' footprint and a 'fuel only' footprint. The 'non-direct fuel' part includes manufacturing and disposal of the boiler, electricity to run the heating system and other auxiliaries.

The reduction is for the entire LPG/BioLPG system versus the entire heating oil system. 'Entire' means it includes hardware and electricity, over the whole life cycle.

The reduction in footprint from LPG 100% to BioLPG 100% is not entirely linear. This is because the calculation model used (a linear programming software called SimaPro) is not completely transparent, so the 'non-direct fuel' and 'fuel only' components cannot be separated perfectly. However, it is very close to linear; in this context, the difference is not meaningful.

Table 11: Footprint comparison of home heating – heating oil versus LPG/BioLPG (t CO2e/lifetime)

Line item	***LPG 100%***	***BioLPG 25%***	***BioLPG 40%***	***BioLPG 50%***	***BioLPG 75%***	***BioLPG 100%***
Heating oil system	131.95	131.95	131.95	131.95	131.95	131.95
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
HO non direct-fuel	9.8	9.8	9.8	9.8	9.8	9.8
LPG non direct-fuel	14.8	14.8	14.8	14.8	14.8	14.8
Heating oil fuel only	122.1	122.1	122.1	122.1	122.1	122.1
LPG/BioLPG fuel only	96.7	78.2	67.1	59.6	41.1	22.6
Reduction	15%	30%	38%	44%	58%	72%

[10] see https://scholar.google.com/citations?view_op=view_citation&hl=en&user=J4rsUqMAAAAJ&citation_for_view=J4rsUqMAAAAJ:WF5omc3nYNoC

4.1.1.2 Electric (storage heating)

The detail behind the reduction is presented below (Table 12). It starts with the footprints of the heating-oil and the LPG systems. The heating oil system's footprint is then 'converted' to an electric system footprint, by substitution of the appropriate efficiency and fuel emission factors. Not all detail is shown in each column, because the results are interpolated from the two 100% extremes. Electricity's non direct-fuel footprint is lower than LPG's (or heating oil's), because the boilers are smaller and require less maintenance (Atlantic Consulting, 2017).

The reduction is for the entire LPG/BioLPG system versus the electric system. 'Entire' means it includes hardware and (operating) electricity, over the whole life cycle.

As with the previous comparison, the reduction in footprint from LPG 100% to BioLPG 100% is not entirely linear, but this negligible difference is lost in the rounding error.

Table 12: Footprint comparison of home heating – electricity versus LPG/BioLPG (t CO2e/lifetime)

Line item	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil system	132.0		132.0			132.0
HO non direct-fuel	9.8		9.8			9.8
Heating oil fuel only	122.1		122.1			122.1
HO efficiency LHV	95%		95%			95%
Electricity efficiency LHV	96%					
HO footprint WTW	87.9					
Electricity footprint WTW	150.8					
Elect fuel only WTW	224.2					
Elect non direct-fuel	5.3					
Electricity system	229.4	229.4	229.4	229.4	229.4	229.4
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
Reduction	51%	59%	64%	68%	76%	84%

4.1.1.3 Coal

The detail behind the reduction is presented below (Table 13). It starts with the footprints of the heating-oil and the LPG systems. The heating oil system's footprint is then 'converted' to a coal system footprint, by substitution of the appropriate efficiency and fuel emission factors. Coal's non direct-fuel footprint is larger than LPG's (or heating oil's), because the boilers are presumed to be larger and to require more maintenance.

The reduction is for the entire LPG/BioLPG system versus the coal system. 'Entire' means it includes hardware and electricity, over the whole life cycle.

As with the previous comparison, the reduction in footprint from LPG 100% to BioLPG 100% is not entirely linear, but this negligible difference is lost in the rounding error.

Table 13: Footprint comparison of home heating – coal versus LPG/BioLPG (t CO2e/lifetime)

Line item	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil system	132.0	132.0	132.0	132.0	132.0	132.0
HO non direct-fuel	9.8	9.8	9.8	9.8	9.8	9.8
Heating oil fuel only	122.1	122.1	122.1	122.1	122.1	122.1
HO efficiency LHV	95%	95%	95%	95%	95%	95%
Coal efficiency LHV	75%	75%	75%	75%	75%	75%
HO footprint WTW	87.9	87.9	87.9	87.9	87.9	87.9
Coal footprint WTW	109.4	109.4	109.4	109.4	109.4	109.4
Coal fuel only WTW	208.0	208.0	208.0	208.0	208.0	208.0
Coal non direct-fuel	22.2	22.2	22.2	22.2	22.2	22.2
Coal system	230.3	230.3	230.3	230.3	230.3	230.3
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
Reduction	52%	60%	64%	68%	76%	84%

4.1.1.4 Peat

The detail behind the reduction is presented below (Table 14). It starts with the footprints of the heating-oil and the LPG systems. The heating oil system's footprint is then 'converted' to a peat system footprint, by substitution of the appropriate efficiency and fuel emission factors. An average of the TTW (combustion) factors for the three types of peat (Table 8, Table 9) is used. Peat's non direct-fuel footprint is larger than LPG's (or heating oil's), because the boilers are presumed to be larger and to require more maintenance.

The reduction is for the entire LPG/BioLPG system versus the peat system. 'Entire' means it includes hardware and electricity, over the whole life cycle.

As with the previous comparison, the reduction in footprint from LPG 100% to BioLPG 100% is not entirely linear, but this negligible difference is lost in the rounding error.

Table 14: Footprint comparison of home heating – peat versus LPG/BioLPG (t CO2e/lifetime)

Line item	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil system	132.0	132.0	132.0	132.0	132.0	132.0
HO non direct-fuel	9.8	9.8	9.8	9.8	9.8	9.8
Heating oil fuel only	122.1	122.1	122.1	122.1	122.1	122.1
HO efficiency LHV	95%	95%	95%	95%	95%	95%
Peat efficiency LHV	75%	75%	75%	75%	75%	75%
HO footprint WTW	87.9	87.9	87.9	87.9	87.9	87.9
Peat footprint WTW	117.9	117.9	117.9	117.9	117.9	117.9
Peat fuel only WTW	224.3	224.3	224.3	224.3	224.3	224.3
Peat non direct-fuel	22.2	22.2	22.2	22.2	22.2	22.2
Peat system	246.5	246.5	246.5	246.5	246.5	246.5
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
Reduction	55%	62%	67%	70%	77%	85%

4.1.1.5 Traditional 'wood fuel stoves'

The carbon footprint of wood-fuelled heat is a controversial topic. The traditional, widely-held view is that wood has a footprint of close to zero. "The tree will grow back," say proponents of this view. "Yes, but you needn't have cut it down in the first place," says an alternative view (Johnson, 2009a), that finds wood's carbon footprint in certain cases to be far higher than that of LPG (Johnson, 2009b)[11].

That said, this comparison adopts the traditional view, which is still held by most EU governments, presumably Ireland's as well. Although we firmly believe in the revisionist approach to wood footprints (and note that it is being widely adopted in the scientific community), we think that in this context (BioLPG) it could be confusing and might overshadow the obvious wins that BioLPG can unequivocally deliver. So, we have used EU figures (Ireland has not published factors for wood, so we have applied factors from the UK).

According to those, even 100% BioLPG still comes in at a higher footprint than wood. The detail behind it is presented below (Table 15). It unfolds in the same sequence as the previous two comparisons.

Table 15: Footprint comparison of home heating – wood versus LPG/BioLPG (t CO2e/lifetime)

Line item	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil system	246.5	246.5	246.5	246.5	246.5	246.5
HO non direct-fuel	111.5	111.5	111.5	111.5	111.5	111.5
Heating oil fuel only	55%	55%	55%	55%	55%	55%
HO efficiency LHV	95%	95%	95%	95%	95%	95%
Wood efficiency LHV	72%	72%	72%	72%	72%	72%
HO footprint WTW	87.9	87.9	87.9	87.9	87.9	87.9
Wood footprint WTW	3.6	3.6	3.6	3.6	3.6	3.6
Wood fuel only WTW	7.2	7.2	7.2	7.2	7.2	7.2
Wood non direct-fuel	22.2	22.2	22.2	22.2	22.2	22.2
Wood system	29.4	29.4	29.4	29.4	29.4	29.4
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
Reduction	-279%	-216%	-178%	-153%	-90%	-27%

4.1.1.6 Natural gas

The detail behind the reduction is presented below (Table 16). It starts with the footprints of the heating-oil and the LPG systems. The heating oil system's footprint is then 'converted' to a natural-gas system footprint, by substitution of the appropriate efficiency and fuel emission factors. Gas's non direct-fuel footprint is assumed to be the same as LPG's, because the systems are quite similar.

The reduction is for the entire LPG/BioLPG system versus the gas system. 'Entire' means it includes hardware and electricity, over the whole life cycle.

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[11] Calor's sponsorship of both studies is very gratefully acknowledged.

As with the previous comparison, the reduction in footprint from LPG 100% to BioLPG 100% is not entirely linear, but this negligible difference is lost in the rounding error.

Table 16: Footprint comparison of home heating – natural gas versus LPG/BioLPG (t CO2e/lifetime)

Line item	*LPG 100%*	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Heating oil system	132.0	132.0	132.0	132.0	132.0	132.0
HO non direct-fuel	9.8	9.8	9.8	9.8	9.8	9.8
Heating oil fuel only	122.1	122.1	122.1	122.1	122.1	122.1
HO efficiency LHV	95%	95%	95%	95%	95%	95%
Nat gas efficiency LHV	102%	102%	102%	102%	102%	102%
HO footprint WTW	87.9	87.9	87.9	87.9	87.9	87.9
Nat gas fprint WTW	64.6	64.6	64.6	64.6	64.6	64.6
Nat gas fuel only WTW	90.4	90.4	90.4	90.4	90.4	90.4
Nat gas non direct-fuel	14.8	14.8	14.8	14.8	14.8	14.8
Nat gas system	105.2	105.2	105.2	105.2	105.2	105.2
LPG/BioLPG system	111.5	93.0	81.9	74.5	55.9	37.4
Reduction	-6%	12%	22%	29%	47%	64%

4.1.2 Other heating

In addition to the home heating comparison above, we also considered 'other heating', i.e. heating in general, based only on published emission factors and not entailing a detailed analysis of specific heating systems.

These reductions (Table 2) were calculated by comparing the well-to-wheel footprints, as published by the authorities, of BioLPG and competing fuels. The precision/accuracy are not as good as the comparisons above for home heating, but they are good enough for public claims.

4.2 Haulage

Calor foresees selling BioLPG into the haulage market as unblended, 100% BioLPG. At this mixture, BioLPG will incur a carbon footprint significantly below that of its competing mono-fuels and fuel mixtures. For marketing statements, we believe the following statements can be asserted:

- ***For heavy duty road vehicles powered by diesel, LNG or CNG, substituting BioLPG can reduce operating footprints by 70+%.***
- ***For heavy duty road vehicles powered by diesel-LPG or diesel-CNG blends, substituting BioLPG (for the LPG or CNG) can reduce operating footprints by around 20%.***

This is a less precise, authoritative finding than for home heating, because the data behind it are less robust. In the following two subsections, first we explain the relative strength of the data, and then we present the detailed results. In a final subsection, we present a potential data source for further analysis.

4.2.1 Why the haulage data are less robust than those for heating

There are three main reasons why haulage data are less robust than those for heating:

- Transport emissions are inherently more variable than heating emissions. Internal combustion engines are much more complicated than boilers and furnaces. A whole host of factors – cylinder design, fuel and air injection methods, lubrication system, speed and torque of testing, load weight, emission controls, drive-test cycle – affect both fuel consumption and emissions significantly. There is enough fine tuning involved that two builds of the exact same automobile can report significantly different emissions for the exact same standardised test! So, it can be very difficult to speak of 'average' performance for a given fuel. A given fuel's good or bad qualities can be overridden by the other factors. Comparisons of fuels, to be meaningful, must hold all other variables close to identical – i.e. other than the fuel, they should compare 'like to like', 'apples to apples', so to speak.
- For heavy duty transport, such like-to-like comparisons are few and far between. Moreover, the few comparisons available tend to be statistically insignificant: say, 1-2 trucks are compared to 1-2 trucks.
- Most studies of heavy duty transport do not include LPG.

4.2.2 Detailed comparison of haulage footprints

Over the years, Atlantic Consulting has investigated transport footprints extensively. So, we reviewed our in-house data and updated our search for new sources. Two came to light that are authoritative enough to support the statements made above:

- For substitution of diesel, LNG and CNG, we relied on a report published jointly by the US (federal) Department of Energy and the Department of Transportation (US Dept of Energy and US Dept of Transportation, 2016). This is clearly an authoritative source, indeed one of the most authoritative anywhere. The data are derived from the 'AFLEET' model[12], developed by DOE's Argonne National Laboratories – one of the leading institutes in this field. However: it is of course US, not UK or European data; the actual comparison is of dustcarts ('garbage trucks', in American), which are a specialised niche of heavy duty vehicles; and the data are not transparent or detailed.
- For substitution of diesel-LPG and diesel-CNG blends, we relied on a report by the Low Carbon Vehicle Partnership sponsored by, among others, the UK Department for Transport (Low Carbon Vehicle Partnership et al., 2017). This is authoritative, and a spot-check of the data show it to be consistent with other authoritative findings. However, only one diesel-LPG truck was tested, and it was compared to a very similar, but not identical truck.

Based on these sources, we came up with the following reduction estimates (Table 17). Because these source data are less robust than those for heating (as noted above), for public pronouncements, we recommend using the statements at the beginning of Section 4.2, rather than the full detail shown below. The full detail is not wrong, but it is more uncertain than it appears.

[12] https://greet.es.anl.gov/index.php?content=afleet

Table 17: Haulage footprints – competing fuels versus LPG/BioLPG

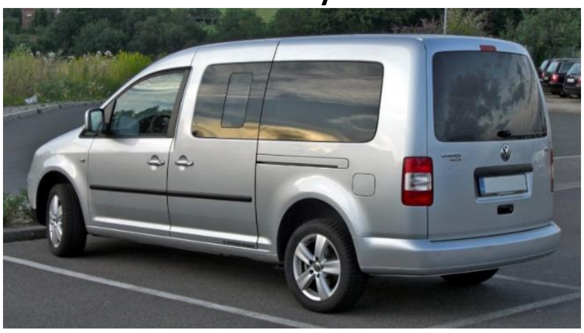
	% reduction in GHGs (CO2e/eq function)			
Substitution of	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Source**
LPG for CNG	3%	33%	78%	US DOE-DOT
LPG for diesel	7%	35%	78%	US DOE-DOT
LPG for LNG	2%	32%	77%	US DOE-DOT
LPG for electric	Adequate data not available			
Diesel-LPG for Diesel	9%	12%	16%	LowCVP
Diesel-LPG for Diesel-CNG	21%	23%	26%	LowCVP

4.2.3 Potential data source for further heavy-duty vehicle comparisons

If Calor choose to broaden their market for BioLPG in transport, a much more robust source of data will be relevant. This is a study sponsored by Calor and Autogas UK, based on a massive vehicle-emissions database maintained by the German Federal Government's Motor Vehicles Agency (Atlantic Consulting, 2014).

Two heavy-duty vehicles covered in this for LPG, diesel, petrol and CNG are the Volkswagen Caddy and the Piaggio Porter. As can be seen in the photos below, these are not what typically would be considered 'haulage' vehicles. Nonetheless, they are considered to be light-heavy-duty, and therefore might be useful comparisons in future.

VW Caddy



Piaggio Porter

4.3 *Forklift footprint comparison*

Calor foresees selling BioLPG into the forklift market. In this application, conventional LPG is already lower-carbon than diesel, and adding BioLPG to the blend makes it even more so. Conventional LPG is higher-carbon than an electric forklift, but adding BioLPG changes this: parity is reached just below a 50% BioLPG blend, and blends above that are lower-carbon than electric (Table 18).

Table 18: Forklift footprints – competing fuel/energy versus LPG/BioLPG

	LPG 100%	*BioLPG 25%*	*BioLPG 40%*	*BioLPG 50%*	*BioLPG 75%*	*BioLPG 100%*
Diesel forklift, operations	9.62	9.62	9.62	9.62	9.62	9.62
Electric forklift, operations & battery	5.82	5.82	5.82	5.82	5.82	5.82
LPG forklift, operations	8.73	7.1	6.1	5.4	3.7	2.0

In the following two subsections, first are presented the sources of data, and then are presented the detailed findings.

4.3.1 *Sources of data*

Almost ten years ago now, Atlantic Consulting published a peer-reviewed comparison of LPG and electric forklifts[13] (Johnson, 2008) that has since been cited in the scientific literature 85 times[14]. In the comparison for this study, we pursued the same approach, but we updated the raw data, using test results published by a leading forklift manufacturer (Jungheinrich, 2015a) (Jungheinrich, 2015b)[15]. The Jungheinrich data are ideally suited to this comparison. They compare forklifts using diesel, electricity and LPG that are otherwise almost completely identical. Each forklift is run through a standard test cycle, VDI 2198[16], specified by the Association of German Engineers (VDI), that measures fuel consumption precisely.

In this context, Calor should be aware of other forklift comparisons that are flawed. Conceivably these might be introduced to the public. We refer here specifically to two publications:

- Flogas has published[17] an undated brochure, which on its second page presents a putative footprint comparison (Figure 1). Except it is not a footprint comparison, because it does not account for the efficiencies of the compared fuels, which vary hugely.
- Polish academics published in 2016 a peer-reviewed comparison in a reputable journal (Fuc et al., 2016) that finds LPG's forklift carbon footprint to be far higher

[13] Calor's sponsorship is gratefully acknowledged

[14] https://scholar.google.com/citations?view_op=view_citation&hl=en&user=J4rsUqMAAAAJ&citation_for_view=J4rsUqMAAAAJ:2osOgNQ5qMEC

[15] Also available at http://www.jungheinrich.com/en/forklift-trucks-at-a-glance/counterbalance-trucks/dfgtfg-425s430s435s/

[16] http://www.vdi.eu/nc/guidelines/vdi_2198-typenblaetter_fuer_flurfoerderzeuge_/

[17] https://www.flogas.co.uk/uploads/asset_file/FLT_Nothing%20else%20stacks%20up.pdf

than electric's and diesel's. Unfortunately, the peer reviewers missed some obvious flaws in the study, namely that the fuel economies of the forklifts are nonsense[18].

Figure 1: Flogas's flawed footprint 'comparison'

	KG CO_2 PER KWHR	INCREASE OVER LPG
Electricity	0.544	+154%
Diesel	0.253	+18%
LPG	0.214	

Source: Carbon Trust Energy and Conversions 2009

4.3.2 Detailed forklift comparison

In our original forklift study (Johnson, 2008), we found that LPG could in some conditions have a similar footprint to electricity (the study did not consider diesel). The study also highlighted the importance of fuel economy, i.e. the efficiency of the forklift. In the intervening years, electric vehicles have become dramatically more efficient. Presumably this is due to the efforts of Tesla and the like in developing battery-electric cars[19].

The upshot is that electric forklifts today are very efficient, relative to LPG or diesel. Electrics consume about one-fifth the energy that LPG or diesel consume in operations (Table 19). This overpowers the other factors in the carbon footprint, making electric forklifts the lowest-carbon of the three types.

Table 19: Efficiency comparison of electric, diesel and LPG forklifts

	Fuel/energy type		
Forklift feature	***Electric***	***Diesel***	***LPG***
Model	EFG 425k	DFG 425s	TFG 425s
Capacity, t	2.5	2.5	2.5
Weight, kg	4,770	3,960	3,960
Battery wt, kg	1,540		
Speed, km/h	NA	19.6	19.6
VDI test results			
Fuel quantity	6.4	3	2.6
Unit	kWh/hr	l/hr	kg/hr
MJ/kWh	3.6		
MJ LHV/l		35.8592	
MJ LHV/kg			46.61
MJ LHV/hr	23.0	107.6	121.2

[18] In November 2016, Atlantic Consulting formally recommended to a Glotech meeting of the WLPGA that they consider refuting the Polish work in a public study. WLPGA aims to do so, as part of a larger study of forklifts planned for publication later in 2018.

[19] See http://www.soci.org/chemistry-and-industry/cni-data/2017/4/electric-dream-revival

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