CO_2

BioLPG's carbon savings

In heating, haulage and forklifts

Atlantic Consulting

August 2017

BioLPG carbon-footprint comparisons

TABLES

FIGURES

1 Summary: BioLPG will offer Calor customers lower carbon

Atlantic Consulting has compared the carbon footprint of BioLPG against competing fuels/energies in three applications: home heating, haulage and forklifts. In each of these applications, BioLPG offers significant reductions in carbon emissions.

1.1 Home heating

Calor foresees selling BioLPG into the home heating market as a 60/40% mixture of LPG/BioLPG. At this mixture, the bio-blend will incur a carbon footprint 22-63% lower than its main competitors, but its footprint will be 178% above that of wood (Table 1Table 8).

Table 1: Home heating footprints – competing fuels versus LPG/BioLPG

	% reduction in GHGs (CO2e/eq function)		
Reduction versus	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***
Heating oil	16%	38%	72%
Electric resistance	48%	62%	83%
Coal	50%	63%	83%
Wood	-280%	-178%	-27%
Natural gas	-7%	22%	64%

1.2 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%.***

1.3 Forklifts

Calor foresees selling BioLPG into the forklift market as a 60/40% mixture of LPG/BioLPG. At this mixture, the bio-blend will incur a carbon footprint 37% lower than diesel, but 10% higher than electricity (Table 15).

Table 2: Forklift footprints – competing fuel/energy versus LPG/BioLPG

	% reduction in GHGs (CO2e/eq function)		
Reduction versus	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***
Reduction, Diesel-LPG	9%	37%	79%
Reduction, Electric-LPG	-58%	-10%	63%

1.4 Organisation of this report

After presenting the basis footprint data in the next two chapters, the following chapter compares the footprints by application (results shown above). A final chapter presents the references.

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 3). 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 3: 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[1]				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 3), because this allocation method is favoured by many analysts and is often applied by the UK

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

Government[2]. 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 3) 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 4).
- These two inputs have been multiplied to generate a weighted average presented in the columns (Table 3) headed with g CO_2e/MJ LHV ***mix***.

The feedstock analysis (Table 4) comes from two sources: (Neste Oyj, 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 4: 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 UK Government (Table 5). For LPG's physical properties, we also have used official UK figures (Table 6). Values for LPG physical properties vary slightly in the scientific and regulatory

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

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

Table 5: LPG carbon footprints, UK

	g CO_2e per				
Life-cycle phase	**MJ LHV**	**MJ HHV**	**kg**	**litre**	**Data source**
Well-to-tank	8.0	7.5	374.7	190.4	(UK Dept of Business Energy & Industrial Strategy, 2016, p 13)
Tank-to-wheel (combustion)	64.0	59.6	2,981.4	1,514.9	(DECC and DEFRA, 2010)
Well-to-wheel/stack	72.0	67.1	3,356.1	1,705.3	Sum of the above

Table 6: LPG physical properties (DECC and DEFRA, 2010)

Property	Value	Unit
LPG heating value	46.61	MJ/kg lower heating value (LHV)
LPG heating value	50.152	MJ/kg higher heating value (HHV)
LPG density	508.13	kg/m3
LPG density	0.50813	kg/litre

3 Competing fuels' footprints

Here are presented the footprints of fuels/energies that compete against BioLPG and LPG (Table 7). Most of them are official figures from the UK Government. A few of them come from (BioGrace, 2015), a database sponsored by the European Commission. The remaining ones come from previous studies of Atlantic Consulting.

Only lower heating value (LHV) footprints are presented, because the entire analysis has been done on this basis.

Higher heating value (HHV) footprints are not presented here, but they are used in some studies and references (often USA-based ones), so readers should always check this when making external comparisons.

Table 7: Competing fuel footprints, WTT and TTS, g CO2e/MJ LHV

	g CO2e/MJ LHV				
Fuel/Energy	*WTT*	*Data Source*	*TTW*	*Data Source*	*WTW*
CNG	8.7	1	56.4	3	65.1
Coal	14.8	1	99.4	3	114.1
Diesel	15.4	1	74.05	4	89.4
Electricity	17.2	1	124.12	1	141.3
Heating oil	14.6	1	74.05	4	88.6
LNG	21.1	1	56.5	5	77.6
LPG	8.0	1	64.0	2	72.0
BioLPG	16.8	6	0.0	6	16.8
Natural gas	7.7	1	56.8	2	64.5
Wood, logs	3.6	2	0	2	3.6
Wood, pellets	3.6	2	0	2	3.6
Key to Data Sources					
Number	*Reference*				
1	(UK Dept of Business Energy & Industrial Strategy, 2016)				
2	(UK DEFRA, 2016)				
3	(BioGrace, 2015)				
4	(Johnson, 2012)				
5	Atlantic Consulting study, unpublished (Qatar or LNG comparison)				
6	(Johnson, 2017)				

4 Footprint comparison

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;
- haulage and
- forklift operation.

For each fuel in each application, we have compared it to three mixtures of LPG/BioLPG:

- 100% LPG
- 40%/60% 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[3]. 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 Home heating

Calor foresees selling BioLPG into the home heating market as a 60/40% mixture of LPG/BioLPG. At this mixture, the bio-blend will incur a carbon footprint 22-63% lower than its main competitors, but its footprint will be 178% above that of wood (Table 8).

Table 8: Home heating footprints – competing fuels versus LPG/BioLPG

	% reduction in GHGs (CO2e/eq function)		
Reduction versus	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***
Heating oil	16%	38%	72%
Electric resistance	48%	62%	83%
Coal	50%	63%	83%
Wood	-280%	-178%	-27%
Natural gas	-7%	22%	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 also cited 9 times[4]. This study estimated the carbon footprint of home heating/hot water systems over the lifetime of a typical boiler in the UK. It includes the

[3] 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.

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

footprints of manufacturing and disposing of the boiler hardware and of the fuels' production.

4.1.1 Heating Oil

The detail behind the 38% reduction is presented below (Table 9). 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, as the final two rows show. Our calculated reduction rounds to 38%, whilst the linear value would be 38.1%. In this context, the difference is not meaningful.

Table 9: Footprint comparison of home heating – heating oil versus LPG/BioLPG

		% reduction in GHGs (CO2e/eq function)				
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Source**	**Comment**
Heating oil system	t CO2e/lifetime	111.51	111.51	111.51	HO study	
LPG/BioLPG system	t CO2e/lifetime	94.0	69.0	31.5	HO study	
HO non direct-fuel	t CO2e/lifetime	8.3	8.3	8.3		est from original HO data
LPG non direct-fuel	t CO2e/lifetime	12.5	12.5	12.5		est from original HO data
Heating oil fuel only		103.2	103.2	103.2		
LPG/BioLPG fuel only	t CO2e/lifetime	81.5	56.5	19.0		
Reduction	real calculated	16%	38%	72%		
	linear		38.1%			

4.1.2 Electric (storage heating)

The detail behind the 62% reduction is presented below (Table 10). 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. Electricity's non direct-fuel footprint is lower than LPG's (or heating oil's), because the boilers are smaller and require less maintenance[5].

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.

[5] Atlantic Consulting investigated this recently as part of a study for an LPG distributor in the Channel Islands.

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 10: Footprint comparison of home heating – electricity versus LPG/BioLPG

		% reduction in GHGs (CO2e/eq function)			
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Source**
Heating oil system	t CO2e/lifetime	111.51	111.51	111.51	
HO non direct-fuel	t CO2e/lifetime	8.3	8.3	8.3	
Heating oil fuel only	t CO2e/lifetime	103.21	103.21	103.21	
HO efficiency LHV		95%	95%	95%	HO study, Table 5
Electricity efficiency LHV		96%	96%	96%	HO study, Table 5
HO footprint WTW	g CO2e/MJ LHV	88.6			
Electricity footprint WTW	g CO2e/MJ LHV	141.3			
Elect fuel only WTW	t CO2e/lifetime	176.0			
Elect non direct-fuel		4.4			Channel Islands study
Electricity system	t CO2e/lifetime	180.4	180.4	180.4	
LPG/BioLPG system	t CO2e/lifetime	94.0	69.0	31.5	
Reduction		48%	62%	83%	

4.1.3 Coal

The detail behind the 63% reduction is presented below (Table 11). 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 11: Footprint comparison of home heating – coal versus LPG/BioLPG

		% reduction in GHGs (CO2e/eq function)			
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Comment**
Heating oil system	t CO2e/lifetime	111.51	111.51	111.51	
HO non direct-fuel	t CO2e/lifetime	8.3	8.3	8.3	
Heating oil fuel only	t CO2e/lifetime	103.21	103.21	103.21	
HO efficiency LHV		95%	95%	95%	
Coal efficiency LHV		75%			
HO footprint WTW	g CO2e/MJ LHV	88.6			
Coal footprint WTW	g CO2e/MJ LHV	106.8			

		% reduction in GHGs (CO2e/eq function)			
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Comment**
Coal fuel only WTW	t CO2e/lifetime	170.2			
Coal non direct-fuel	t CO2e/lifetime	18.8			assume 50% bigger than LPG
Coal system	t CO2e/lifetime	189.0	189.0	189.0	
LPG/BioLPG system	t CO2e/lifetime	94.0	69.0	31.5	
Reduction		50%	63%	83%	

4.1.4 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)[6].

That said, this comparison adopts the traditional view, which is still reflected in UK government figures. 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 the UK government figures.

According to those, even 100% BioLPG still comes in at a higher footprint than wood. The detail behind it is presented below (Table 12Table 11). It unfolds in the same sequence as the previous two comparisons.

Table 12: Footprint comparison of home heating – wood versus LPG/BioLPG

		% reduction in GHGs (CO2e/eq function)			
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Comment**
Heating oil system	t CO2e/lifetime	111.51	111.51	111.51	
HO non direct-fuel	t CO2e/lifetime	8.3	8.3	8.3	
Heating oil fuel only	t CO2e/lifetime	103.21	103.21	103.21	
HO efficiency LHV		95%	95%	95%	
Wood efficiency LHV		72%			
HO footprint WTW	g CO2e/MJ LHV	88.6			
Wood footprint WTW	g CO2e/MJ LHV	3.6			
Wood fuel only WTW	t CO2e/lifetime	6.0			
Wood non direct-fuel	t CO2e/lifetime	18.8			assume 50% bigger than LPG

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

		% reduction in GHGs (CO2e/eq function)			
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Comment**
Wood system	t CO2e/lifetime	24.8	24.8	24.8	
LPG/BioLPG system	t CO2e/lifetime	94.0	69.0	31.5	
Reduction		-280%	-178%	-27%	

4.1.5 Natural gas

The detail behind the 22% reduction is presented below (Table 13Table 11). 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.

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 – natural gas versus LPG/BioLPG

		% reduction in GHGs (CO2e/eq function)				
Line item	**Units**	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	***Source***	**Comment**
Heating oil system	t CO2e/lifetime	111.51	111.51	111.51		
HO non direct-fuel	t CO2e/lifetime	8.3	8.3	8.3		
Heating oil fuel only	t CO2e/lifetime	103.21	103.21	103.21		
HO efficiency LHV		95%	95%	95%	HO study, Table 5	
Nat gas efficiency LHV		102%	102%	102%	HO study, Table 5	avg of the 2 values in the table
HO footprint WTW	g CO2e/MJ LHV	88.6				
Nat gas fprint WTW	g CO2e/MJ LHV	64.5				
Nat gas fuel only WTW	t CO2e/lifetime	75.6				
Nat gas non direct-fuel	t CO2e/lifetime	12.5				assume same as LPG
Nat gas system	t CO2e/lifetime	88.1	88.1	88.1		
LPG/BioLPG system	t CO2e/lifetime	94.0	69.0	31.5		
Reduction		-7%	22%	64%		

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 datasource 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[7], 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

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

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 14). 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.

Table 14: Haulage footprints – competing fuels versus LPG/BioLPG

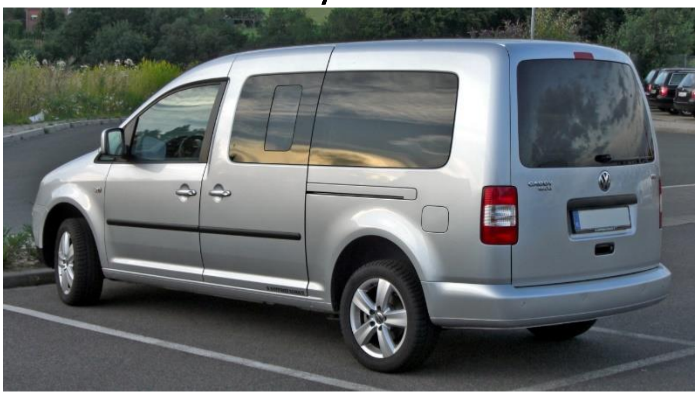
	% reduction in GHGs (CO2e/eq function)			
Substitution of	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***	**Source**
LPG for CNG	3%	33%	78%	US DOE-DOT
LPG for diesel	7%	35%	78%	US DOE-DOT
LPG for LNG	2%	32%	77%	US DOE-DOT
LPG for electric	Adequate data not available			
Diesel-LPG for Diesel	9%	12%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

4.2.3 Potential datasource 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 as a 60/40% mixture of LPG/BioLPG. At this mixture, the bio-blend will incur a carbon footprint 37% lower than diesel, but 10% higher than electricity (Table 15).

Table 15: Forklift footprints – competing fuel/energy versus LPG/BioLPG

	% reduction in GHGs (CO2e/eq function)		
Reduction versus	***LPG 100%***	***BioLPG 40%***	***BioLPG 100%***
Reduction, Diesel-LPG	9%	37%	79%
Reduction, Electric-LPG	-58%	-10%	63%

In the following two subsections, first we present the sources of data, and then we present 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[8] (Johnson, 2008) that has since been cited in the scientific literature 76 times[9]. In the comparison for this study, we pursued the same approach, but we updated the raw data from a forklift manufacturer (Jungheinrich, 2015a) (Jungheinrich, 2015b)[10].

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, specified by the Association of German Engineers (VDI), that measures fuel consumption precisely. Despite the recent scandal where Volkswagen and

[8] Calor's sponsorship is gratefully acknowledged

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

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

other carmakers fiddled tests of diesel emissions, it boosts authority that the data are 'Made in Germany'.

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[11] 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 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[12].

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[13].

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

[12] 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 appears to have tabled the idea.

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

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 16). This overpowers the other factors in the carbon footprint, making electric forklifts the lowest-carbon of the three types.

Table 16: 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

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