Current and Future Lifecycle Emissions of Key 'Low Carbon' Technologies and Alternatives

Final Report

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Project carried out for the Committee on Climate Change (CCC)

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Context for the work

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- In previous advice on carbon budgets, the Committee on Climate Change (CCC) has identified scenarios for how these budgets might be met. These scenarios include ‘low-carbon’ technologies which reduce emissions at point-of-use relative to counterfactual.

- The CCC has commissioned Ricardo-AEA to undertake an analysis considering lifecycle emissions (LCEs) for various technologies in several sectors, going beyond the point-of-use. Results from this study will feed into the UK consumption emissions report and will inform review of the fourth carbon budget (late 2013).

- Several technologies and sub-technologies in the power, residential and transport sectors have been covered for this analysis. This reports outlines the results from this analysis and reports current and future LCEs

- The environmental impacts of low carbon technologies have been evaluated by many studies over the years. A life cycle analysis (LCA) approach from cradle-to-grave is usually undertaken to allow an identification of the hotspots along the life cycle of a technology where emissions are large and to be able to provide an understanding of where these key emissions are located. Some of the impact categories usually evaluated include cumulative energy demand, global warming potential, eutrophication potential, acidification potential and human toxicity. The current study focusses on the GWP impact category and so only GHG LCEs are evaluated.

- The current study does not aim to undertake a detailed LCA of the different technologies. The overall objective is to provide an estimate of current LCEs based on circumstances specific to the UK and to use this estimate to project LCEs into the future (to 2050). Current LCEs are broken down into relevant categories which will allow an investigation of the influence of key geographical parameters on overall emissions and to allow the separation of these emissions into UK and non-UK emissions. This will then allow an investigation of different scenarios and how these emissions can be reduced.

Objectives

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Key questions

The study aims to answer the following questions

- What are the lifecycle emissions associated with each of the technologies be in the UK?
- How do the lifecycle emissions compare to the counterfactual?
- Do the emissions arise in the UK, or are they embedded in imported goods? If embedded, where are they imported from?
- How might the emissions change in the future?
- How could the emissions be reduced?

These questions have been answered by reviewing existing research, extracting information on the key parameters which influence LCEs, and then exploring potential changes in these parameters in the future (to 2050). Scenario representing potential changes in the parameters were explored using a simple calculation tool, focussing on the most important drivers. Life cycle stages which do not contribute significantly to overall LCEs were excluded.

In order to achieve the objectives above, the following tasks have been undertaken.

Task	Description
Task A	Establish range of lifecycle emissions for technologies deployed in the UK under current conditions*
Task B	Identify key sources and locations of these emissions
Task C	Develop scenarios for potential changes in lifecycle emissions to 2050

* Many of the studies reviewed were UK-based. This, however, was not always possible and so the review covered studies outside the UK.

Scope

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Location and time horizon

The present study evaluates life cycle GHG emissions in the UK to 2050. The technologies covered are listed in the table below.

Sector	Counterfactual	Low carbon technologies	Sub-technologies
Power	Combined cycle gas turbine (CCGT)	Coal CCS	Pulverised coal (PC) with post combustion capture (post- CC) via amines
			Integrated gasification combined cycle (IGCC) with pre-combustion capture (pre- CC) VIA Selexol
		Gas CCS	CCGT with post- CC via amines
		Nuclear	Pressured water reactor (PWR)
		Wind	Onshore
			Offshore
		Solar	Mono-crystalline silicon
			Poly-crystalline silicon
			Cadmium telluride
Residential	Gas boiler	Heat pumps	Air source heat pumps
			Water source heat pumps
	Solid wall insulation		
Transport	Internal combustion engine	PHEV Car	Plug-in hybrid electric vehicle
		BEV Car	Battery electric vehicle
		FCEV Artic HGV	Hydrogen fuel cell electric vehicle

For each of the technologies, existing studies (with UK focus) were reviewed. The key lifecycle stages (hotspots) were identified and modelled into a LCE calculation spreadsheet to estimate current and future LCEs. Life cycle stages which did not contribute significantly to overall LCEs were not considered as part of the analysis.

Overall approach

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- **Literature review**:
  - Existing literature was reviewed. Data on assumptions made by the different studies and overall life cycle emissions was collected and compared. A range of overall life cycle emissions and associated assumptions by the different studies was identified. Data was presented graphically to allow comparison of results. Outliers were explained based on an understanding of the assumptions stated in the studies reviewed.
  - The studies reviewed were narrowed down based on transparency and clarity of assumptions and availability of data. Overall life cycle emissions were broken down by life cycle stage. The key life cycle stages (hotspots) were identified.
  - The literature relevant to the UK was reviewed to allow an understanding of the geographical and other factors which could influence LCEs.
  - Data was collected on material and energy requirements for the key life cycle stages.
- **Spread sheet calculation tool**:
  - A simple spreadsheet calculation tool was developed to allow the estimation of current and future (to 2050) LCEs based on UK-specific and technology-specific data.
  - Technology-specific parameters (e.g. power and capture plant specific parameters) were used with material and energy requirements (collected from the literature) to allow estimation of material / energy requirements for the specific plant investigated here.
  - Material and grid emission intensities were estimated for the years 2010, 2020, 2030, 2040 and 2050 and for different world regions and used to estimate current and future LCEs
  - GHG emissions were calculated by stage and for different years as show below.

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Material requirement (kg)	X	Material carbon intensity (kg)	=	CO_2 emissions (kg $CO_{2,e}$) in a given year for a given life cycle stage
Energy requirement (MJ)	X	Energy intensity (kg $CO_{2,e}$/MJ)	=	CO_2 emissions (kg $CO_{2,e}$) in a given year for a given life cycle stage

Overall approach

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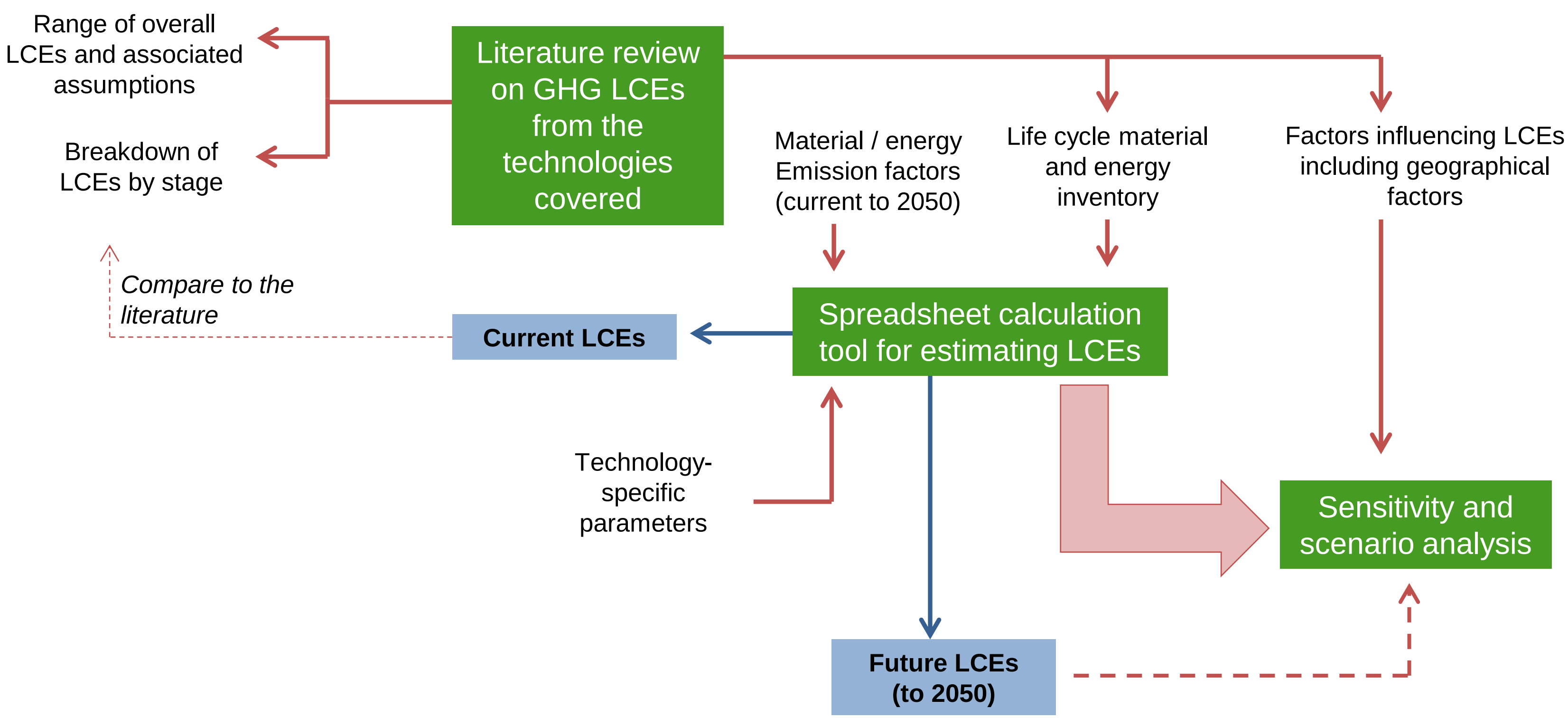
The calculation tools developed were used to undertake sensitivity analysis on key parameters. Results are reported by life cycle stage and by location (UK vs. non-UK emissions)



Sources of data

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Parameters	Sources
Technology parameters (e.g. load factor, lifetime, annual activity, etc.)	CCC modelling and recent publications
Material requirements, kg Energy requirements, kg	Review of LCA studies
Material emission factors, kg CO_2 /kg Transport emission factors, kg CO_2 /kg.km Grid intensity, kg CO_2 /kWh UK grid intensity, kg CO_2 /kWh	Bath University ICE Database IEA ETP 2012 data CCC modelling Other sources

- IEA data provides current and future (to 2050) emissions intensities for iron & steel, aluminium, chemicals and cement and for different world regions (e.g. OECD, non-OECD). However, this data only includes direct and indirect emissions but not upstream emissions. The CCC provided data for UK emissions from different sectors: steel, cement, and ammonia and also grid intensity to 2050 but this also did not include LCEs.
- The carbon intensities in the Bath University ICE database include upstream emissions and so the IEA data for the key materials above was used in combination with the Bath University ICE database (only includes current but not future carbon intensities, for the UK only) to develop estimates of current and future carbon and grid intensities.

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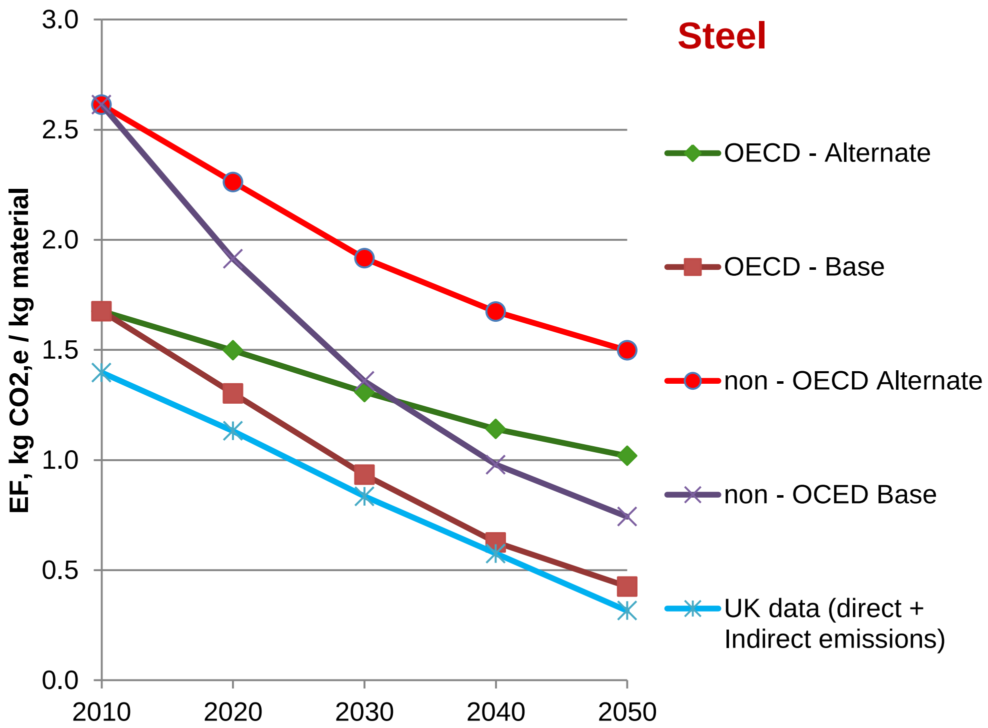
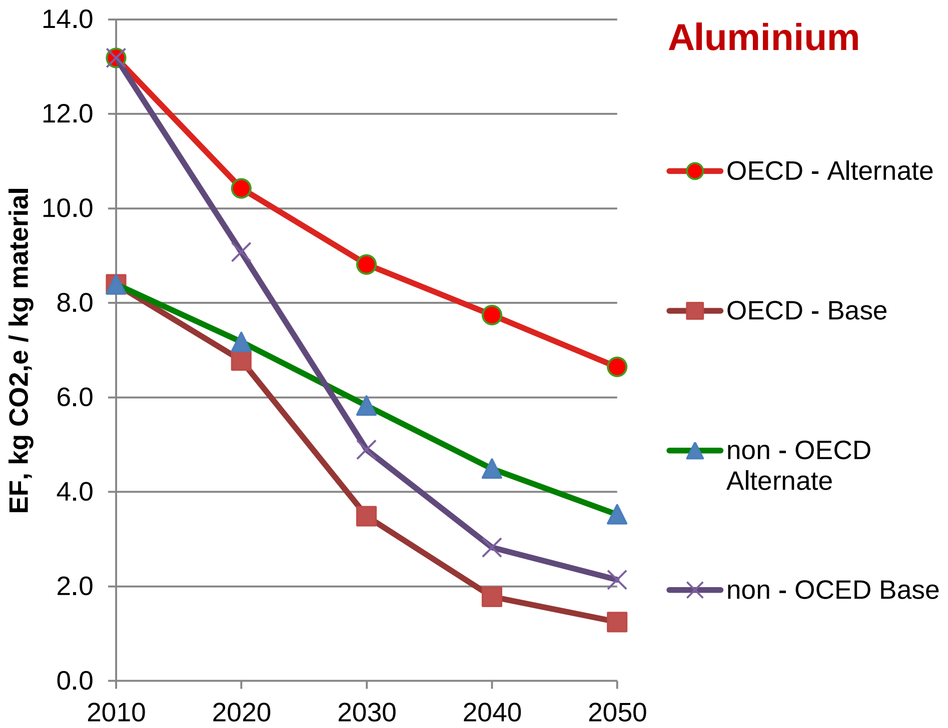
IEA Data

The IEA data for steel includes steel production rates as well as amount of CO_2 produced (tonnes) to 2050. Direct and indirect emissions from both blast furnace / basic oxygen (BF/BO) and electric arc furnace (EAF) technologies can be calculated. Electricity consumption figures and grid intensities for different regions (to 2050) are used to estimate the EAF EF. The BF/BO emission factor (EF) is also estimated. A weighted average EF for steel for different regions is then calculated.

A similar approach is used to estimate an EF for both direct and indirect emissions from the production of aluminium for different regions and to 2050. For the chemicals sector, production rates and total CO_2 emissions are used to estimate EF accounting for both direct and indirect emissions. The EFs derived from the IEA data were then used to scale the Bath ICE data for different regions and over time





Report structure

- The following are discussed in the report for each of the technologies
  - Overview of life cycle stages
  - Range of overall LCEs in the literature
  - Key assumptions in the literature and an account for discrepancy in the reported LCEs
  - Breakdown of LCEs in selected previous studies
  - Identification of the ‘hotspots’ in the life cycle and key conclusions from the literature
  - Definition of the base scenario
    - Comparison of results from the present study to the literature
    - Base scenario: current and future LCEs
    - UK vs non-UK emissions for the base scenario
  - List of sensitivities
  - Sensitivity results and identification of key influencing parameters
  - Conclusions: major contributors to LCEs, where they are located and how they can be reduced

The Power Sector

Coal with Carbon Capture and Storage (CCS)

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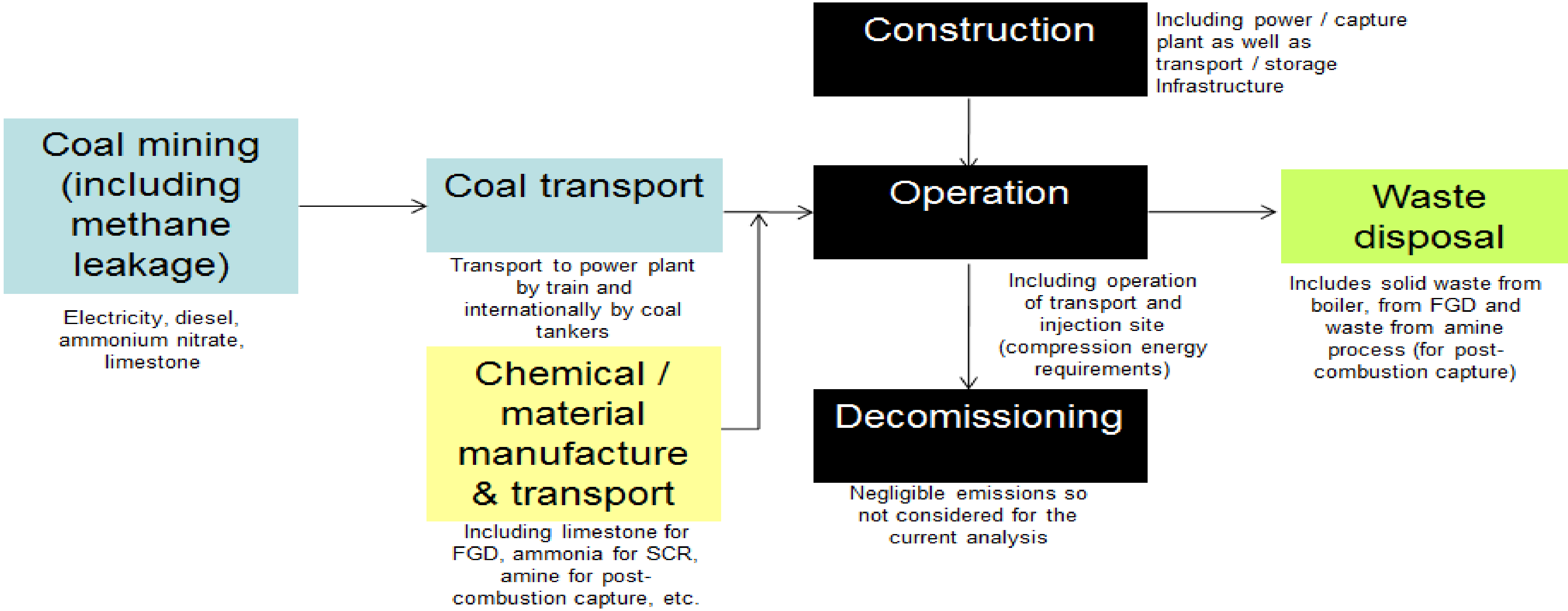
The Coal CCS life cycle

Current and future LCEs were estimated for coal power plants with CCS. The study covered both pulverised coal (PC) combustion with post combustion capture and integrated gasification combined cycle (IGCC) with pre-combustion capture.

The coal life cycle consists of three main stages: construction, operation and decommissioning. The addition of the CO_2 capture plant, CO_2 transport pipeline and CO_2 injection facilities is expected to increase the construction related LCEs of a CCS plant relative to a non-CCS plant. In addition, the increased energy and material requirements of a the CCS plant, as well as additional waste disposal needs, will also increase the operational LCEs.



The addition of CCS technology might be expected to reduce the direct CO_2 emissions from combustion by 90%. However, the energy consumption associated with the capture plant (for solvent regeneration, CO_2 compression, etc.) means additional coal is required (relevant to the power plant without CCS) to make up for this power loss. the net reduction in direct emissions is therefore less than 90%. In addition, the additional coal required leads to an increase in upstream coal mining and transport emissions. The transport and storage of CO_2 may also require re-compression of CO_2 leading to additional LCEs.

Scope covered in the literature on coal CCS

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- Many studies have been undertaken over the past decade on life cycle analysis of coal power plants with CCS. The studies cover different coal generation technologies including sub-critical and super-critical pulverised coal (PC) with post-combustion capture and integrated gasification combined cycle (IGCC) with pre-combustion capture.

- For PC power plants, the technology of choice is usually amine-based chemical absorption, although others have been considered (e.g. hindered amine solvent KS-1 (Muramatsu, 2002), membranes and cryogenics (Khoo, 2006), oxyfuel (Viebahn,2007)).

- IGCC with pre-combustion capture is investigated in the literature to a lesser extent (Marx et al., 2011).

- The fuel considered in the majority of studies is hard coal. In some studies (Viebahn, 2007; NEEDs, 2008), lignite is also considered.

- Stages with negligible impacts are usually not included. Khoo (2006), Viebahn (2007), Korre (2009) and Schreiber (2009) did not include construction and decommissioning in their assessment. Spath (2004) included construction emissions but excluded decommissioning and waste disposal. Muramatsu (2002), Viebahn (2007) and NEEDs (2008) did not include downstream (waste disposal) emissions in the analysis.

Review of the literature on coal CCS

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- Coal mining and transport is always included in the analysis and is thought to be a 'hotspot' in terms of LCEs of the coal CCS fuel cycle. Coal mining involves the extraction of coal which requires fuel (diesel) as well as electricity. In addition, deep (underground) mining requires limestone while surface (open-cast) mining requires ammonium nitrate (Spath, 1999). Underground coal mining is associated with high methane leakage rates. Open cast mining, on the other hand, is associated with very low methane leakage rates (Ecoinvent, 2007). The source of coal plays an important role in estimating overall life cycle emissions as different countries have different share of deep / surface mining and consequently, different leakage rates. Coal is transported from international sources to the UK via tankers. Coal is transported in the country of source as well as in the UK by trains.

- The main material required for the operation of coal power plants is coal. For PC power plants equipped with selective catalytic reduction (SCR) for NOx removal and flue gas desulphurisation (FGD) for SO_2 removal, additional materials are also required. This includes ammonia for SCR and limestone for FGD. It should also be noted that both SCR and FGD (in addition to the coal handling and steam cycle equipment) are associated with energy consumption which leads to reduction in power output of the power plants. Typical estimates are 0.5% of gross capacity for the coal pulveriser, 0.2% for the steam cycle pumps, 1.5% for fans, 0.5% for SCR and 1.5% for FGD. For the current study, the analysis is based on the net efficiency of the power / capture plant and so these energy penalties are already accounted for.

Assumptions in the literature

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- Net efficiencies for the power/capture plant in the studies reviewed range from 29 to 42% for PC with CCS (hard coal) 32-48% for IGCC with CCS. The higher ends for both PC and IGCC are too optimistic for current available technologies. These higher figures, however, refer to efficiencies in the future as a result of technological progress.

- The capture efficiency considered is mostly 90%. Some studies (Khoo, 2006) considered 95%-98% for chemical absorption while Lombardi (2003) considered 85%. Viebahn (2007) considered a capture efficiency of 88% for both post-combustion capture and pre-combustion capture (with Rectisol).

- Several studies also consider CO_2 transport and storage. Most studies consider pipeline for transport with distances ranging from 50 km to 500 km. Khoo (2006) also considered ship transport for a distance of 100 km. The share of LCEs from the transport and storage phases ranges from less than 1% to about 10%. The wide range is due to differences in assumptions of fuel and power generation / capture technology.

- The following slide shows a list of recent studies available on life cycle analysis of coal CCS. These tables also show the associated assumptions for each of the studies. The range in the literature for both PC with post-combustion capture and IGCC with pre-combustion capture is shown on the next slide[1].

- A comprehensive review of the literature on the LCA of CCS is given in the IEA report ‘Environmental evaluation of CCS using life cycle assessment’ (2010).

Study comparison – PC + post-combustion capture

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Range of key assumptions and corresponding LCEs in the literature for PC with post- CC

Study	Year	Technology	Fuel	Net capacity, MW	Net efficiency	Capture technology	CO_2 capture rate	LCEs, g CO_2,e/kWh	Comment
Muramatsu	2002	PC	Hard coal	-	30.8%	MEA	90%	-	
	2002	PC	Hard coal	-	33.3%	KS-1	90%	-	
Spath	2004	PC - SC	Bituminous	457	31.2	MEA	90%	247	US
IEA	2006	Advanced SC	Bituminous	666	34.8%	MEA	-	NA	
Khoo	2006	PC	Hard coal	-	-	MEA	95%	79	High capture rate, assumptions not clear
Viebahn	2007	SC	Hard coal	570	40%	MEA	88%	262	Germany
Odeh	2008	PC – SC	Hard coal	335	30%	MEA	90%	255	UK
Koornneef	2008	PC – SC	Hard coal	-	-	MEA	90%	243	Netherlands
Pehnt	2008	SC	Lignite	500 – 800	27.8%	MEA	90%	190	
NEEDs	2008	PC	Lignite	800	42%	MEA	90%	156	
	2008	PC	Hard coal	500	42%	MEA	90%	213	
Schreiber	2009	SC	Hard coal	391	32.6	MEA	90%	247	Germany
Korre	2009	-	-	-	-	-	-	179	
NETL	2010	SC	Hard coal			MEA	90%	245	
Singh	2011	SC	Hard coal	400	33.2	MEA	90%	220	Norway
Hammond	2011	SC	Hard coal			MEA	90%	310	Injection in oil fields for EOR

SC = supercritical

Study comparison – IGCC + pre-combustion capture

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Range of key assumptions and corresponding LCEs in the literature for IGCC with pre- CC

Study	Year	Technology	Fuel	Net capacity, MW	Net efficiency	Capture technology	CO_2 capture rate	LCEs, g CO_2,e/kWh	Comment
Doctor	2001	IGCC + pre- CC	Bituminous	110	-	Glycol	90%	490	High value. Not clear what the net efficiency is (solvent is glycol so energy penalty should be low). Low capacity.
Lombardi	2003	IGCC pre- CC	Hard coal	288	38.8	DEA+MDEA	85%	358	Very high despite higher net efficiency but low capture rate
IEA	2006	IGCC + pre- CC	Bituminous	683	-	-	-		
Viebahn	2007	IGCC + pre- CC	Hard coal	590	42%	Rectisol	88%	244	
Odeh	2008	IGCC + pre- CC	Hard coal	471	32%	Selexol	90%	167	
NEEDS	2008	IGCC + pre- CC	Lignite	400	46%	-	90%	138	
			Hard coal	400	48%	-	90%	171	
Pehnt	2008	IGCC + pre- CC	Lignite	500-800	38.7%	Selexol	90%	140	
NETL	2010	IGCC + pre- CC	Hard coal			Selexol	90%	218	

Some studies were selected for further comparison as these stated assumptions clearly for the different life cycle stages. The results are shown in the graphs on slides 20 and 21.

Overall Life Cycle Emissions – PC + CCS

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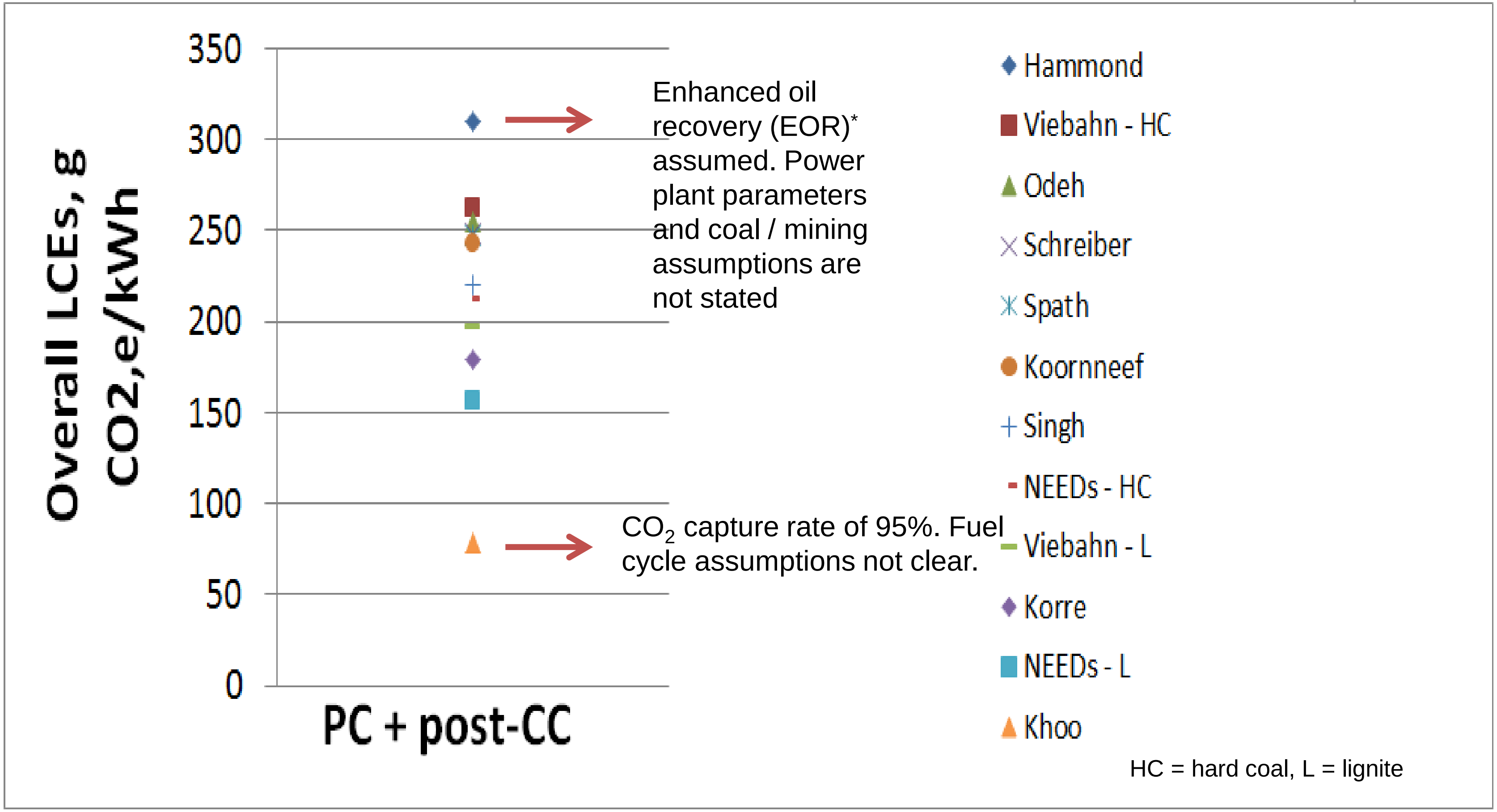

* Enhanced oil recovery (EOR) is a technique used to recover oil trapped in the pore spaces. Gas injection is the most common technique for EOR. The injection of captured CO_2 into depleted oil gas fields improves the flow of trapped oil. As the CO_2-oil mixture reaches the surface, the CO_2 is separated and recycled back to recover more oil. A proportion of CO_2 remains sequestered in the oil field. The separation of CO_2 from oil requires energy and so is expected to add to LCEs. Energy requirements for EOR applications are expected to be higher than for gas fields and aquifers. This study covered LCEs from injection into gas fields and aquifers but not oil fields.

For PC with post- CC, studies report a range of 80-300 g $CO_{2,e}$/kWh. Most studies show a range of 220-250 g/kWh.

Overall Life Cycle Emissions

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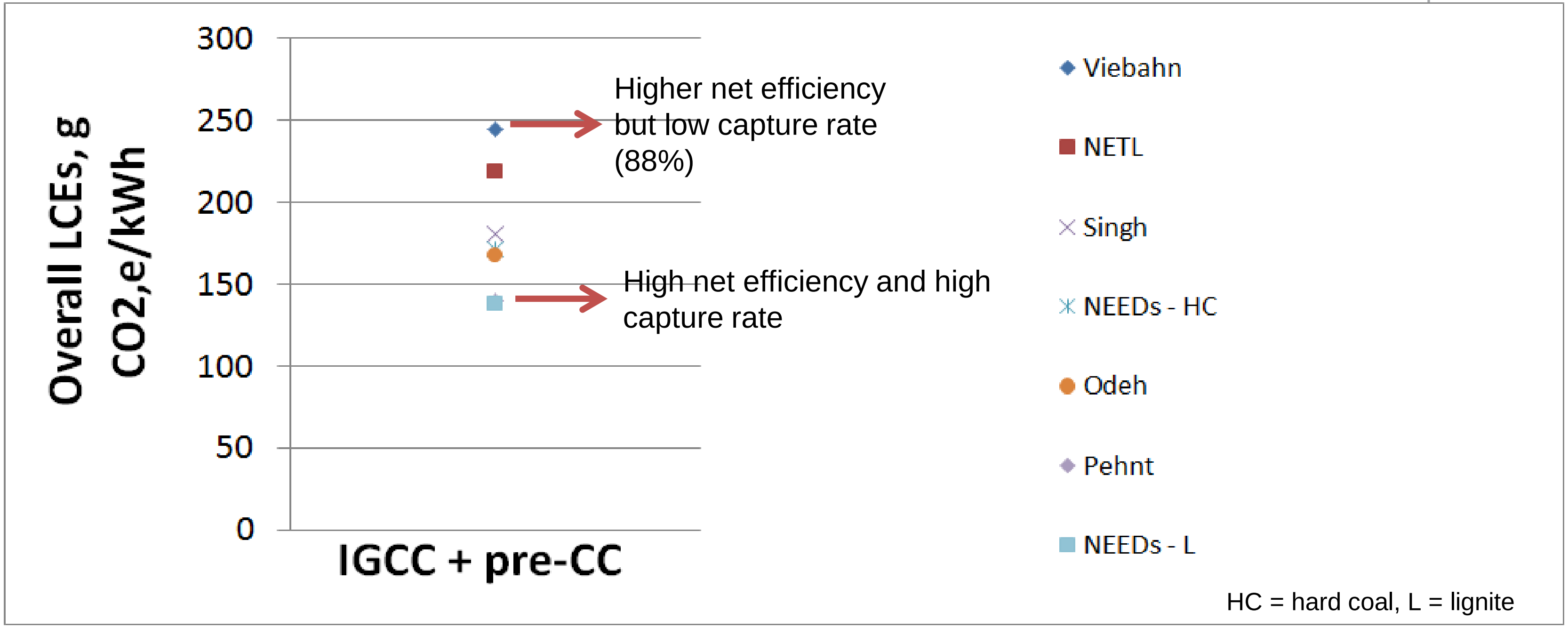

For IGCC with pre- CC, studies report a range of 140-250 g $CO_{2,e}$/kWh.

- ❑ There is a range in the overall LCEs reported in the literature as shown on slides 20 and 21. The key parameters leading to this discrepancy are
  - Assumptions about the source of coal including its composition and energy content. The carbon content (%) of the coal plays an important role in deciding combustion emissions (Odeh and Cockerill assumed 60% carbon content in coal, Schreiber assumed 69%, the NEEDs study assumed 64% while Spath assumed 68%).
  - Whether methane leakage is considered as part of the analysis or not, and the level of assumed leakage
  - The power plant efficiency. The plant load factor and lifetime both have negligible effects on LCEs.
  - The energy penalty and CO_2 capture efficiency assumptions.
  - Different LCA methodologies (e.g. process-based analysis, input/output-based analysis or hybrid methodology)

Breakdown of life cycle emissions

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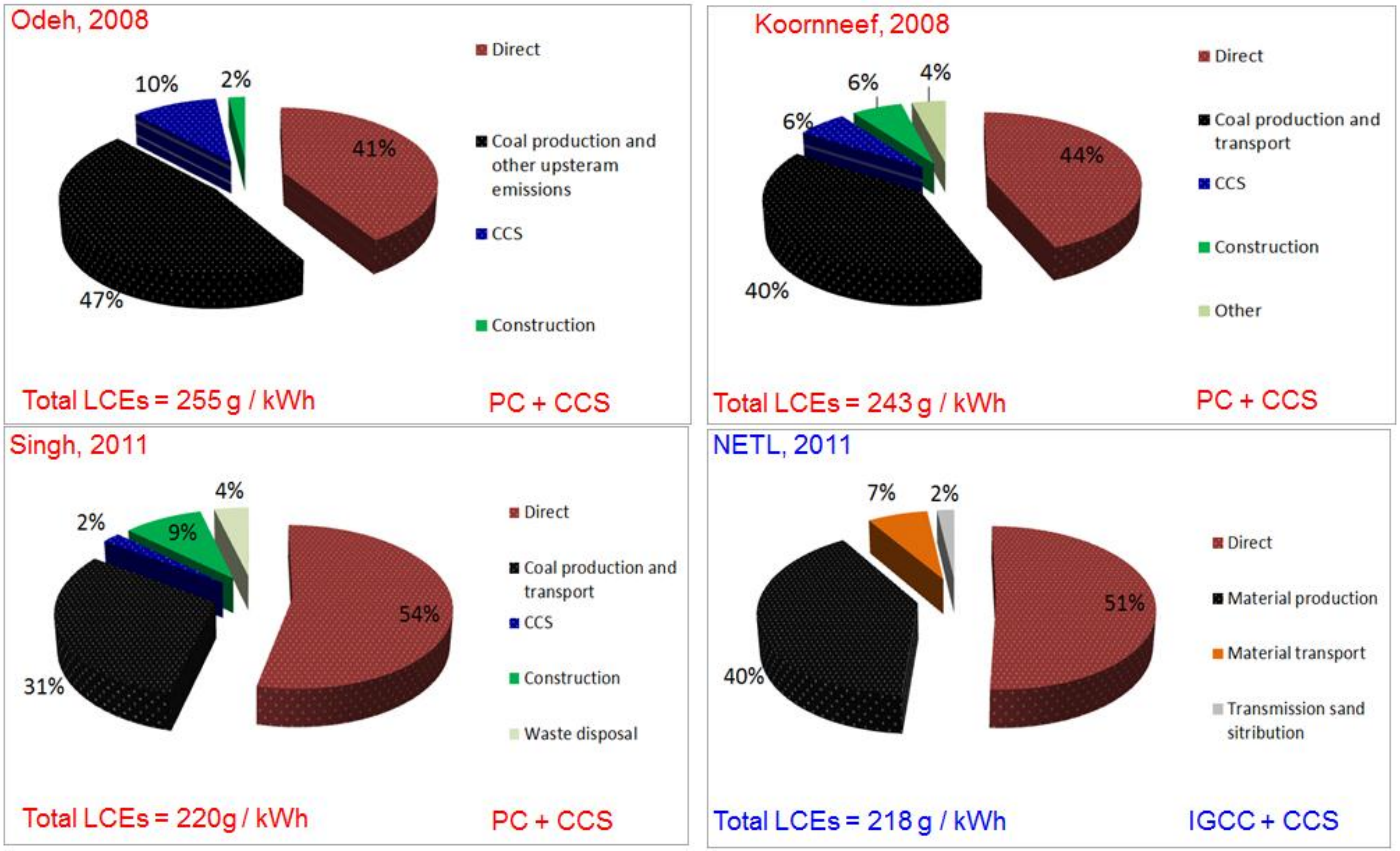
The breakdown of LCEs from selected studies is shown below. It can be observed that direct emissions are in the range 40-55%. The wide variation in combustion emissions can be attributed to variations in power plant efficiency, capture efficiency and the type and properties of coal.

Coal mining and other upstream emissions make up 30-45% of overall LCEs. The variation can be attributed to different assumptions about the source of coal, methane leakage and other stages of the life cycle.



Current emission hotspots in the coal CCS life cycle

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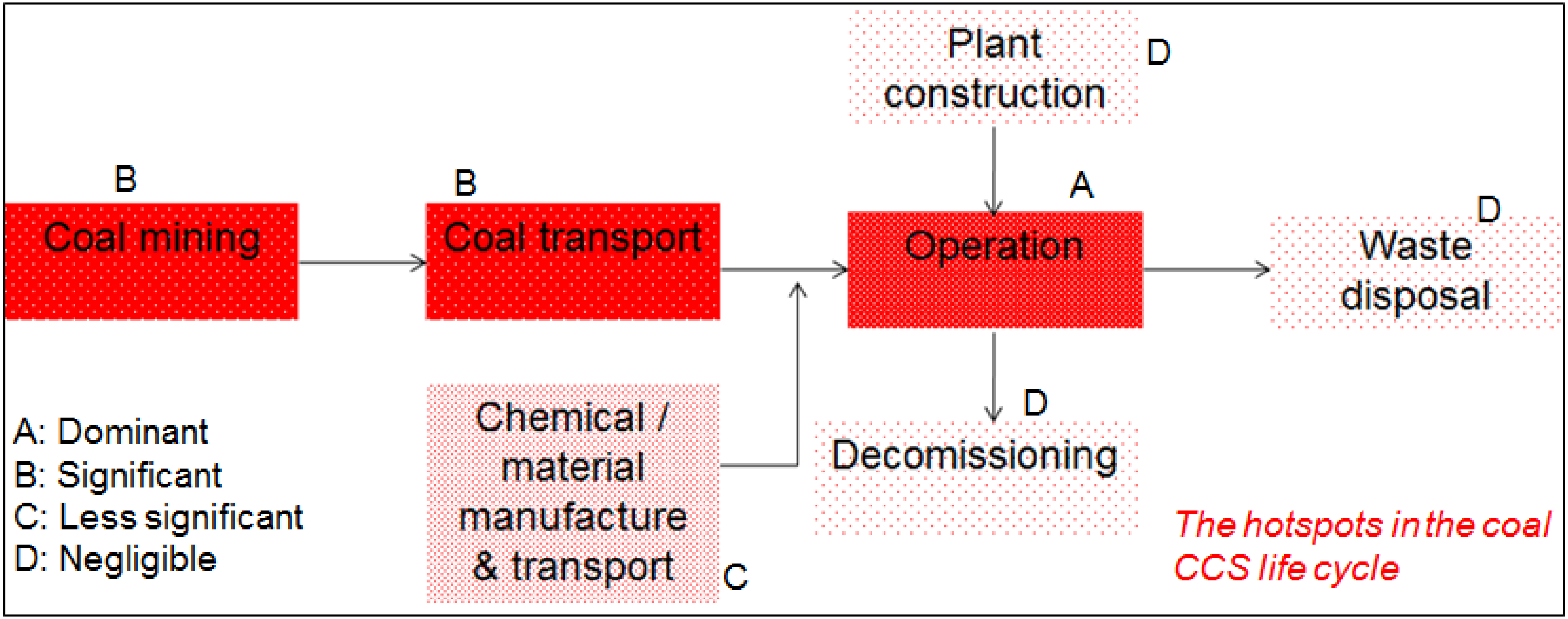
- Based upon the review of the literature, the key hotspots in the coal CCS life cycle i.e. the most important sources of LCEs, can be identified. These are shown below. Emissions from construction, decommissioning and waste disposal are negligible in comparison to other parts of the coal CCS life cycle.



Geographical factors

- Certain emissions will relate to geographical factors.

- The construction of the power / capture and the transport / storage infrastructure will require significant amounts of metal and concrete. The main metals are steel, iron, aluminium and copper. For a UK power plant, these may either be sourced in the UK or internationally. Studies in the literature usually consider that raw materials are sourced locally within the country where the plant is constructed. However, life cycle emissions from the construction phase are currently (and are expected to remain in the future) low in comparison to other LCEs and so the source of raw materials will have negligible effect on overall LCEs.

- Other than combustion (40-55% of total LCEs for coal CCS), the main contributor to LCEs is coal mining and transport. The location where the coal is mined is an important factor in determining overall LCEs.
  - The mining process requires electricity and diesel. Electricity is needed for fans, pumps, drills, crushers, conveyers and shovels (for surface mining) while diesel is required for trucks, bulldozers and loaders. Studies in the literature report electricity and diesel consumption separately. Gas with a methane concentration larger than 35% can be used for electricity generation onsite. However, not all sites recover methane from coal mines or generate power onsite. In cases where grid electricity is used, future LCEs will depend on the rate of the decarbonisation of the grid in the country of origin. The present study assumes grid electricity is used.
  - The coal energy content and heating value will also depend on where coal is sourced.
  - Different countries have different shares of surface and deep mining which leads to different methane leakage rates. Future LCEs will depend on plans in different countries on capturing methane from coal mines.
  - The transport distance and thus associate transport emissions will depend on where coal is imported from.

- Most of the steam coal used in UK power plants currently is imported. About 93% of the coal imported in the UK comes from three countries: Russia (46%), Colombia (30%), and the US (17%). In future, it is expected that the share of Russian coal will increase.

- Energy requirements for the transport pipeline and storage site will depend on whether the CO_2 is stored in the UK or overseas. This study assumes that all CO_2 will be stored in the UK and so all transport / storage emissions will be UK emissions.

- The UK has strong chemical industry and so it is expected that the chemicals required for the capture plant and other processes will be manufactured in the UK.

Base case scenario assumptions summary

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The table below summarises the assumptions that have been used in the base case scenario in the current study. The base case assumes material and grid emission factors based on the IEA ETP 2 scenario. Additional base case condition have been defined for the source of coal, methane leakage rates. Injection is gas fields is assumed. CO_2 transport via pipeline for 300 km is assumed.

Parameter	Base scenario assumption
Power plant parameters	As below (based on Parson Brinckerhoff)
Raw material carbon intensity	Base – based on the IEA 2 degrees scenario
Grid intensity	Base – based on the IEA 2 degrees scenario
Source of coal	The base scenario assumes that coal to the power plant is all imported with 46% from Russia, 30% from Colombia, 17% from the US and 7% from other countries.
Methane leakage rates	Based on current status
Capture plant	Chemical absorption via MEA, 2.34 kg MEA/t CO_2 captured. 90 % capture rate.
CO_2 transport	By pipeline, 300 km (100 km onshore), leakage rate of 0.026% per 1000 km is assumed.
CO_2 storage	Injection gas fields

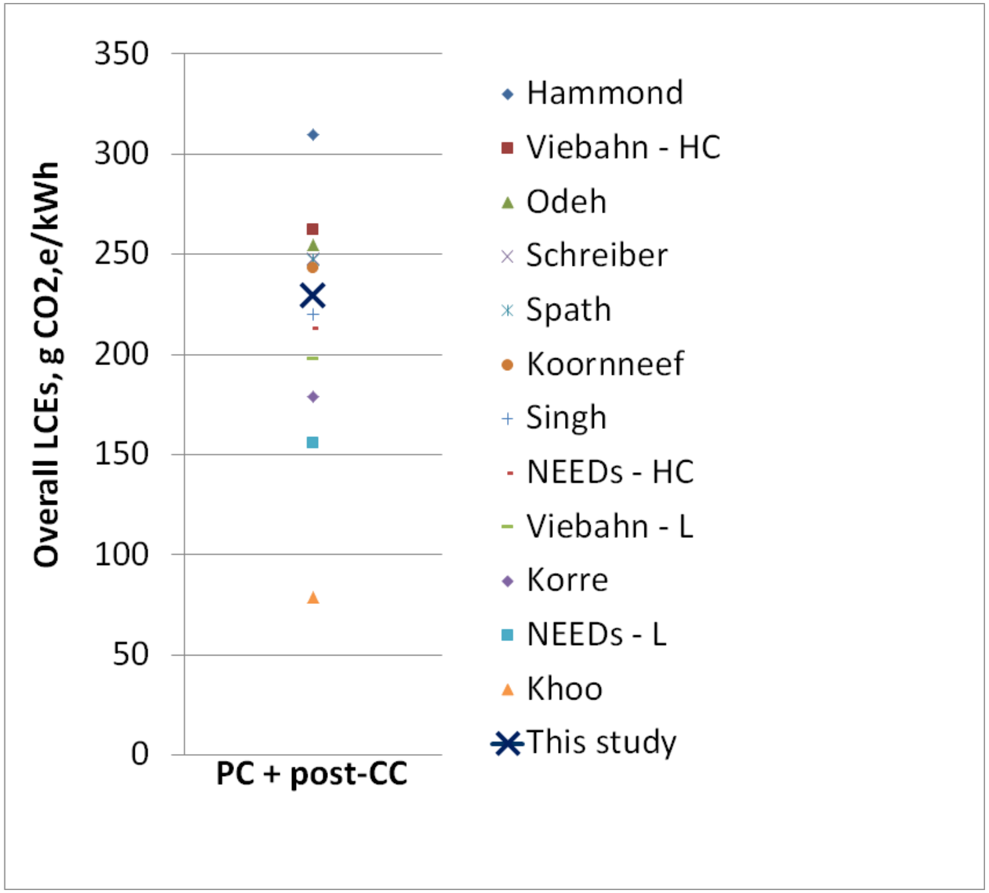
Note: the base case scenario assumes that electricity used is not generated on site but is taken directly from the grid.

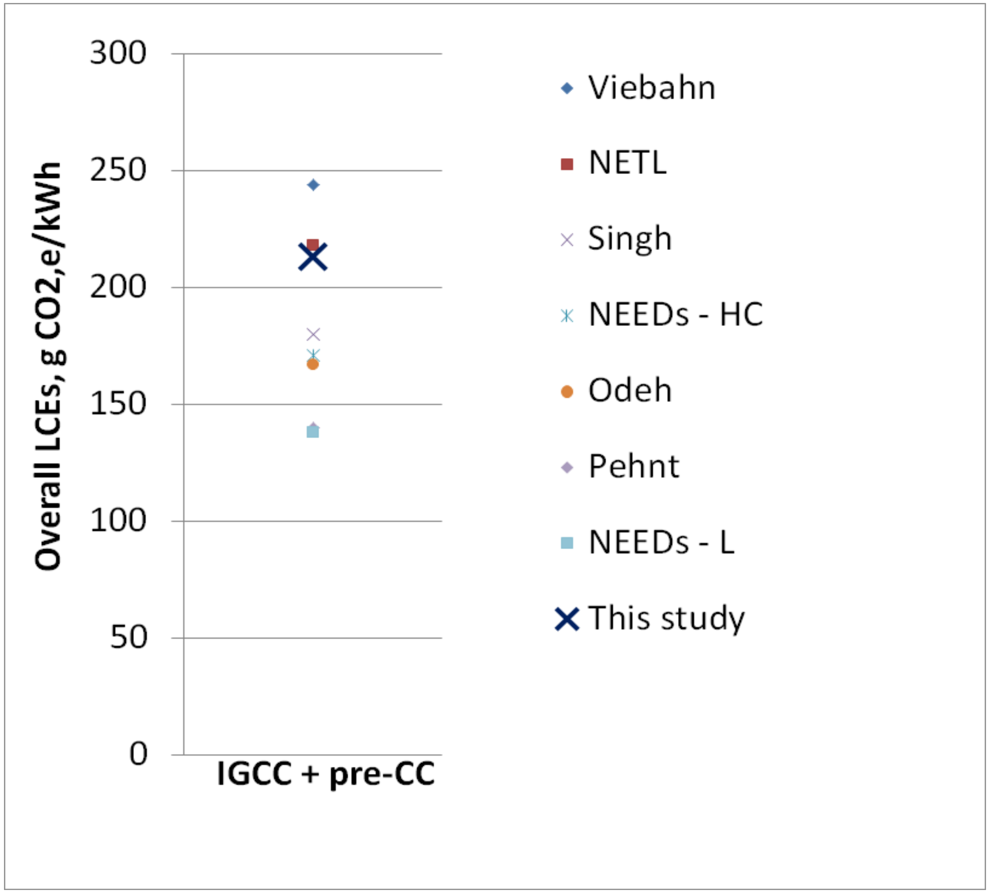
Parameter	Advanced PC + post- CC	IGCC + pre- CC
Capacity (MW)	1600	820
Load factor (%)	100%	100%
Availability	95.8%	89.8%
Net power efficiency*	35%	35%
Lifetime (years)	30	30

* Energy consumption by CO_2 capture and other processes with in the power plant are already accounted for

Comparison with previous studies

In our base case scenario, the estimated current-year LCEs are 229 g $CO_{2,e}$/ kWh for PC + post- CC and 213 g $CO_{2,e}$/ kWh for IGCC + pre-CC. This is in agreement with LCEs provided by previous studies.





Base case scenario: Current LCEs (PC with CCS)

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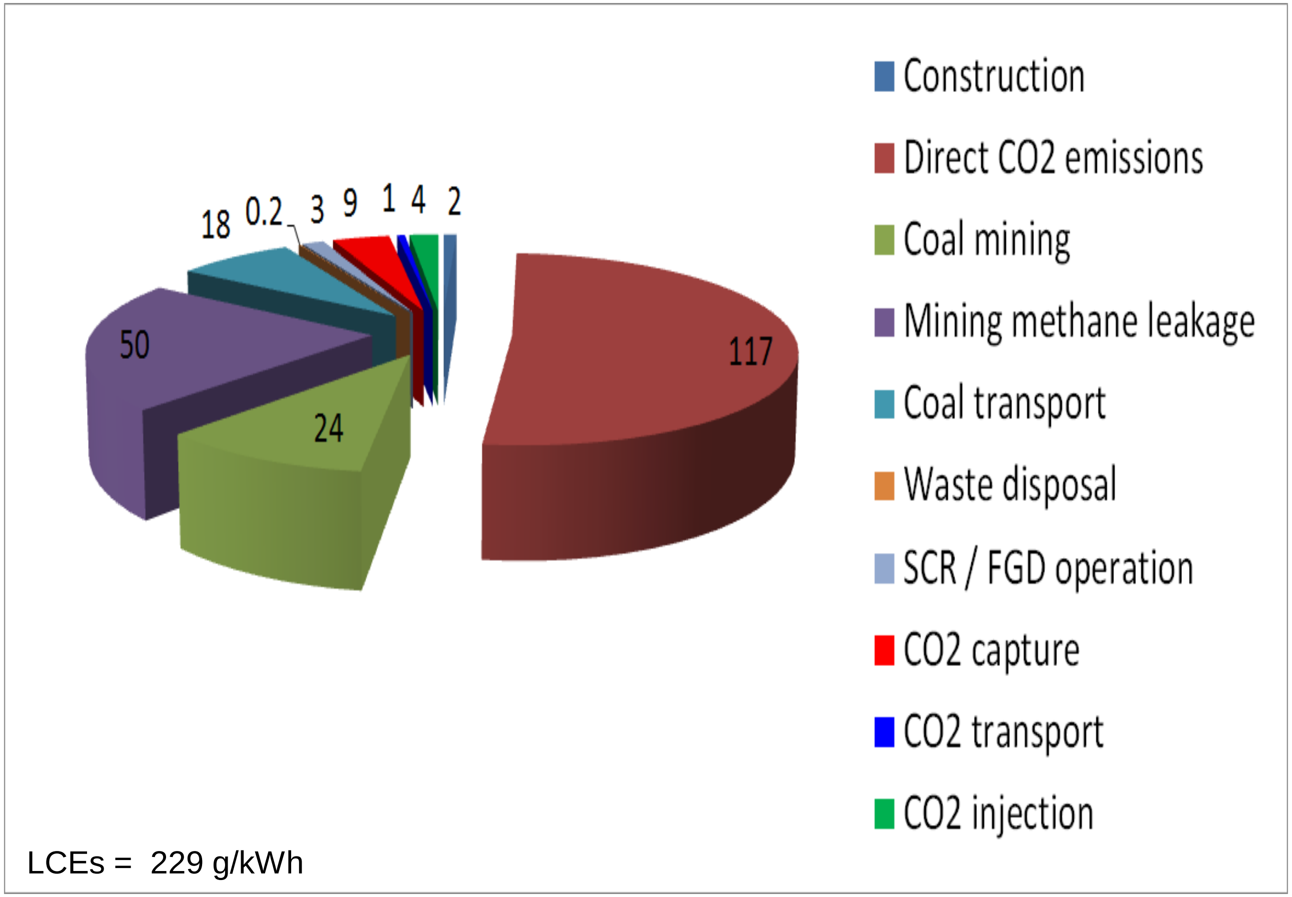
Combustion emissions make up about 50% of overall LCEs for PC with CCS.

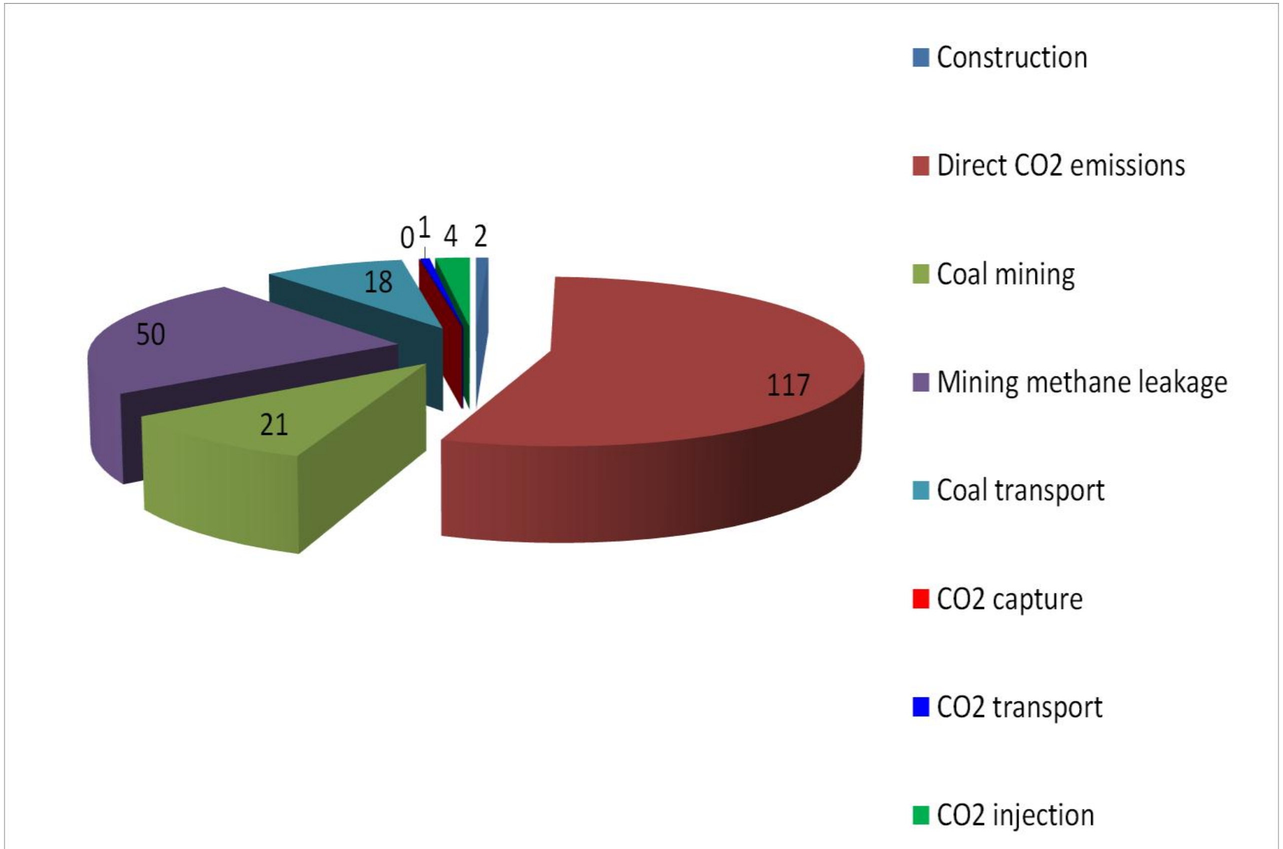
Mining methane leakage is the major contributor of all non-combustion emissions making up 45%.



Base case scenario: Current LCEs (IGCC with CCS)

Combustion emissions make up about 55% of overall LCEs for PC with CCS.

Mining methane leakage is the major contributor of all non-combustion emissions making up 52%.



LCEs = 213 g/kWh

Base case: Current and future LCEs

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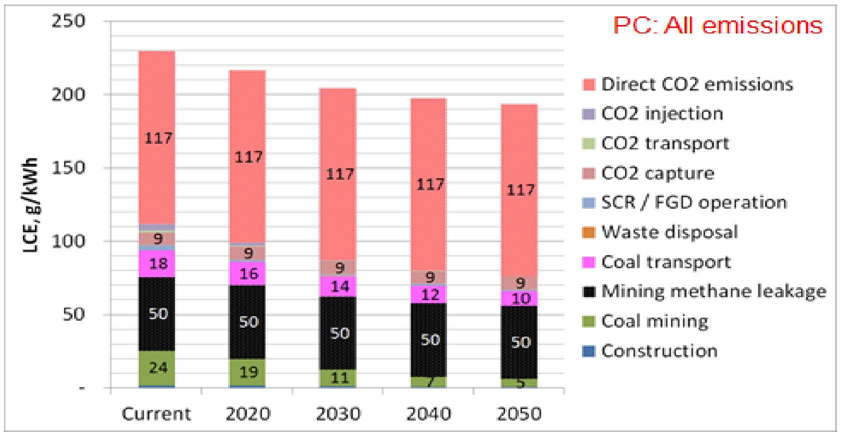
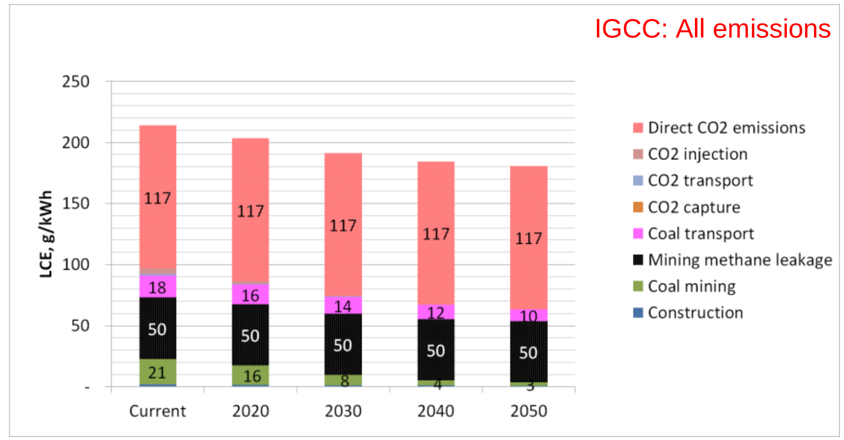
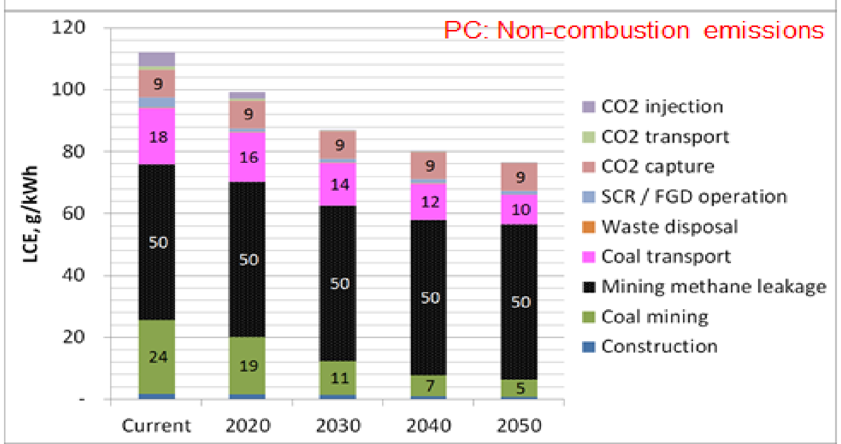
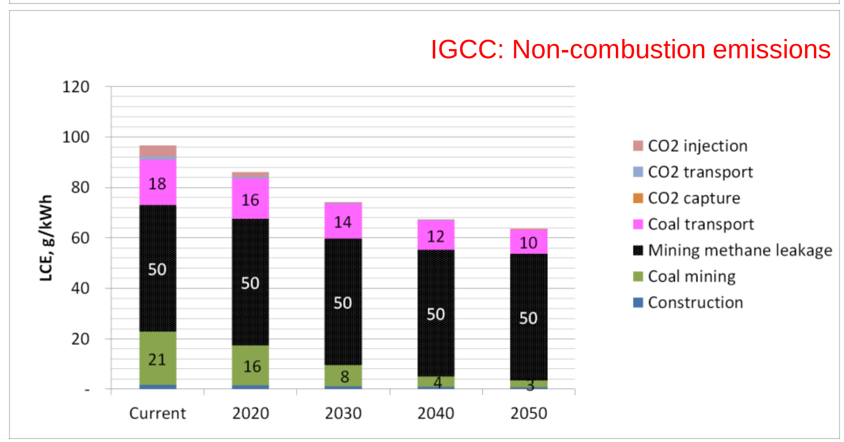
- In 2050, overall LCEs (including combustion) reduce from 229 to 194 g $CO_{2,e}$/kWh for PC with CCS and from 213 g $CO_{2,e}$/ kWh to 181 g $CO_{2,e}$/ kWh for IGCC with CCS.
- The reduction is mainly attributed to reduction in grid intensity at the mining location. As % of total mining LCEs, electricity-related emissions make up 11% of total current and about 3% of total 2050 LCEs.
- Reduction in LCEs is also caused by reduction in the transport emission factors (for coal tanker and train transport).
- The results above assume no improvement in power plants efficiency or capture plant efficiency over time and so the reduction shown in the base scenario is mainly attributed to projected reduction in material, transport and grid emission factors (according to 2° scenario). Transport emission factors t-CO_2/t.km) are assumed to reduce overtime as a result of more efficient means of transport (i.e. higher loading and lower fuel consumption per trip).









Location of emissions: Base scenario

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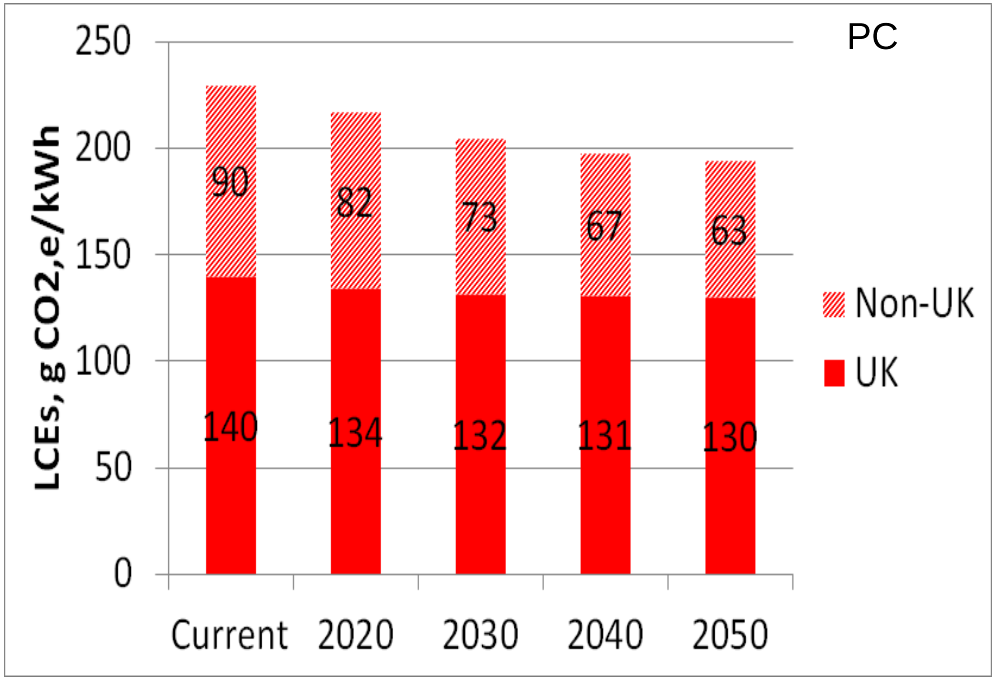
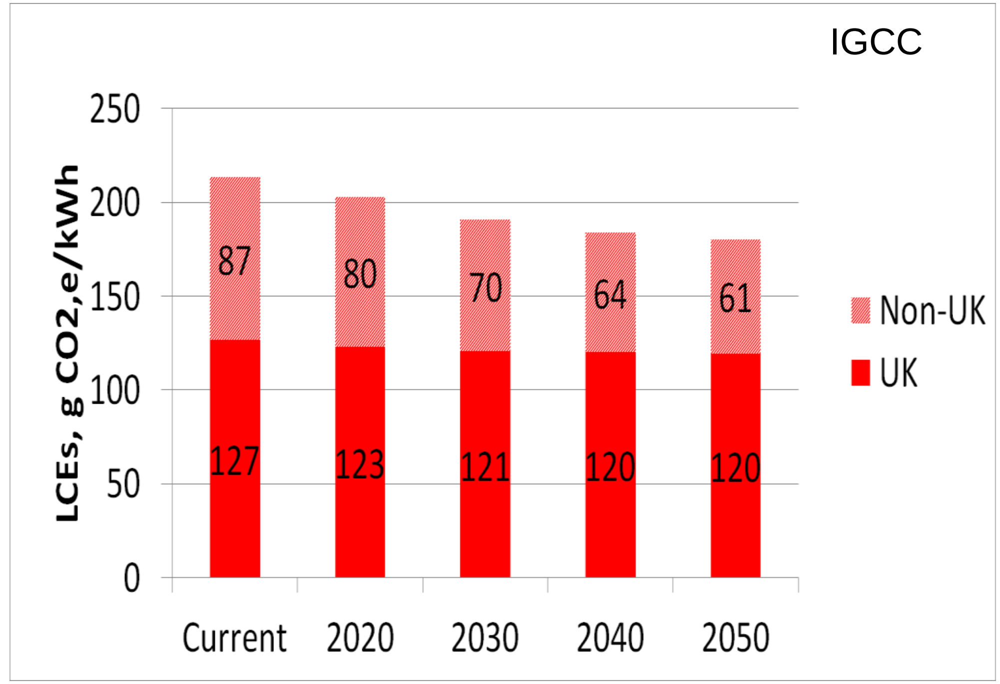
Our analysis suggests that, currently, about 60% of total LCEs could be UK-based. In 2050, the share of UK-based emissions increases for both technologies. These estimates assume no improvement in the power plant efficiency and so direct emissions from combustion remain the same.





- Direct CO_2 emissions as well as CO_2 transport and storage operational emissions (i.e. electricity consumption and CO_2 leakage from transport pipeline) arise in the UK.
- Mining emissions, on the other hand, are non-UK emissions. The estimates shown above assume that:
  * materials used in the construction of the plant are sourced in the UK (these are negligible)
  * all chemicals used by the power and capture plant are sourced in the UK (emissions are not significant)
  * emissions from coal transport by tanker are non-UK emissions (about 5-10% of total coal transport emissions)

Sensitivity analysis: scenario definitions

RICARDO-AEA

Several sensitivities were tested in order to identify the key parameters which could influence the overall LCEs. These are listed in the table below.

Scenario	Parameter tested	Description
Scenario 1: Base	As described above	
Scenario 2	Alternate scenario for material carbon and grid intensity (based on IEA's 4 degrees scenario)	This includes carbon intensity of construction material as well as other chemicals used in the operation of the power / capture plant. It also includes increase in carbon intensity of the grid in the UK and at the mining site.
Scenario 3	Assuming the share of coal from other countries (7% in base scenario) is replaced by Russian coal thus increasing share of Russian coal to 53%. Colombia and US remain as in Base case	The share of coal from Russia has been increasing over the past decade due to the lower sulphur (S) content (about 0.2-0.4% S). Low S coal is sought after by power plants that need to meet the SO_2 emission standards (400 mg/m^3) but have not installed flue gas desulphurisation (FGD) equipment (which is the case for many power generators in the UK). Almost half of UK imports (mainly steam coal) currently comes from Russia. It is expected that this trend will continue in the future as demand for low sulphur coal reduces.

Sensitivity analysis: scenario definitions

RICARDO-AEA

Table 14 Cont'd

Scenario	Parameter tested	
Scenario 4	5 % reduction in average methane leakage rate per tonne of coal mined for Russia (from 9.2 to 8.7 kg CH_4/t coal) and the US (from 3 to 2.85 kg CH_4/t coal). This gives a weighted average methane leakage rate reduction from 5.2 kg CH_4 to 5 kg CH_4/t coal. No significant reduction is assumed or Colombia as all is surface mining.	Globally, coal mining is responsible for 8% of total methane emissions. The leading countries with methane leakage are China (14 Mt/year), Russia (3 Mt/year) and the US. If no action is undertaken to recover methane from coal mines, methane leakage will grow as more coal is mined. According to the IEA, it is expected that methane leakage rates in the long-term will be reduced (IEA, Coal mine methane in Russia, 2009). It is not clear, however, how methane leakage rates will change in the future as this depends on legislation and potential economic benefits from methane recovery. The methane from an underground mine can be recovered for a variety of applications. The feasibility of economically recovering methane will depend on several factors including the amount of methane produced from the mine, purity of the gas stream, and mine location. This study assumes a small reduction in methane leakage rate assuming sites will utilise coal bed methane for some onsite generation.
Scenario 5	20% reduction in energy penalty (i.e. improvement in power plant net efficiency)	Research on new solvents and better system integration is underway to reduce energy consumption associated with the capture process. Currently, for PC plants, the efficiency of the power plant reduces by about 25% when CO_2 capture (MEA-based) is installed. For IGCC with pre- CC, the efficiency reduces by about 15%. This scenario assumes that the net power plant efficiency will increase to 38% for PC with post–CC and 36% for IGCC with pre- CC. This assumes 20% reduction in energy penalty and does not account for improvement in the efficiency of the base plant (i.e. PC and IGCC without CO_2 capture)

Sensitivity analysis: scenario definitions

RICARDO-AEA

Table 14 Cont'd

Scenario	Parameter tested	
Scenario 6	Reduction of capture efficiency to 85%	Base scenario assumption is 90%. Applied on a large scale, the technology may not perform as anticipated. NER300 sets a threshold of 85% so this will be tested.
Scenario 7	Consumption of MEA solvent is reduced from 2.34 kg/t CO_2 captured to 1.6 kg/t CO_2	Effort is underway to reduce consumption of amine solvents. The IPCC Special report on CCS (2005) reports a figure of 1.6 kg amine / t CO_2
Scenario 8	Injection and storage of CO_2 in a saline aquifer instead of a gas field	Gas fields as well as saline aquifers are potential candidates for CO_2 storage. Initially, storage will most likely be in oil and gas fields.

The length and leakage rate of the CO_2 transport pipeline can be tested using the spreadsheet calculation tool but these were found to have negligible effect and so were not included as sensitivities in this report.

Sensitivity analysis: PC with CCS

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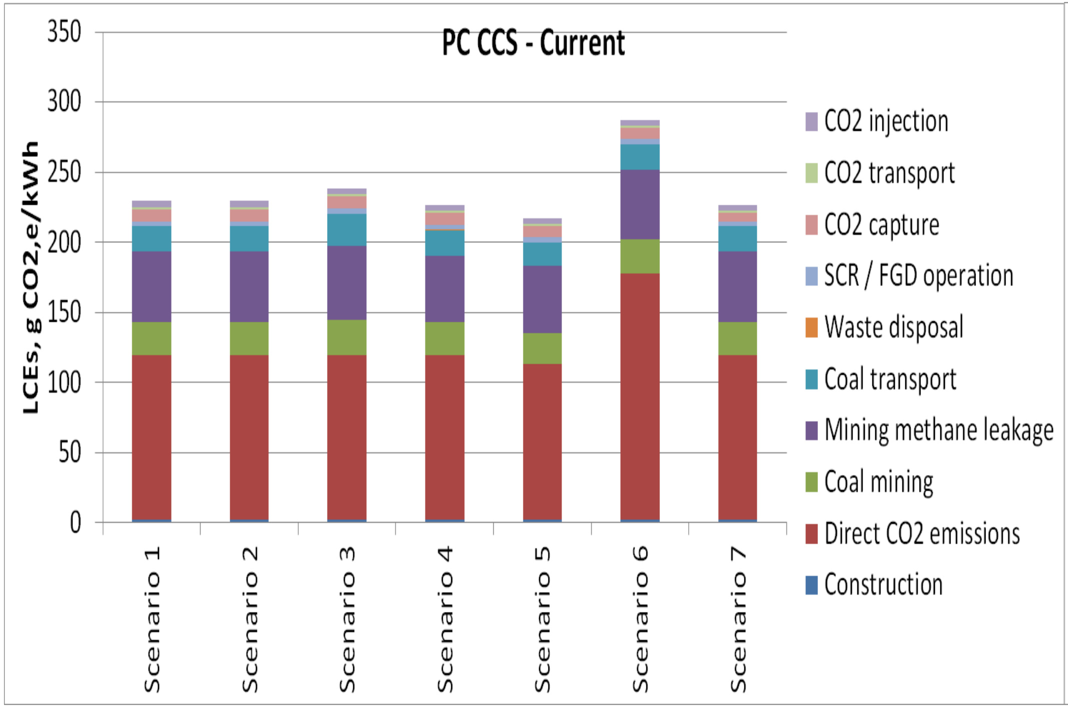
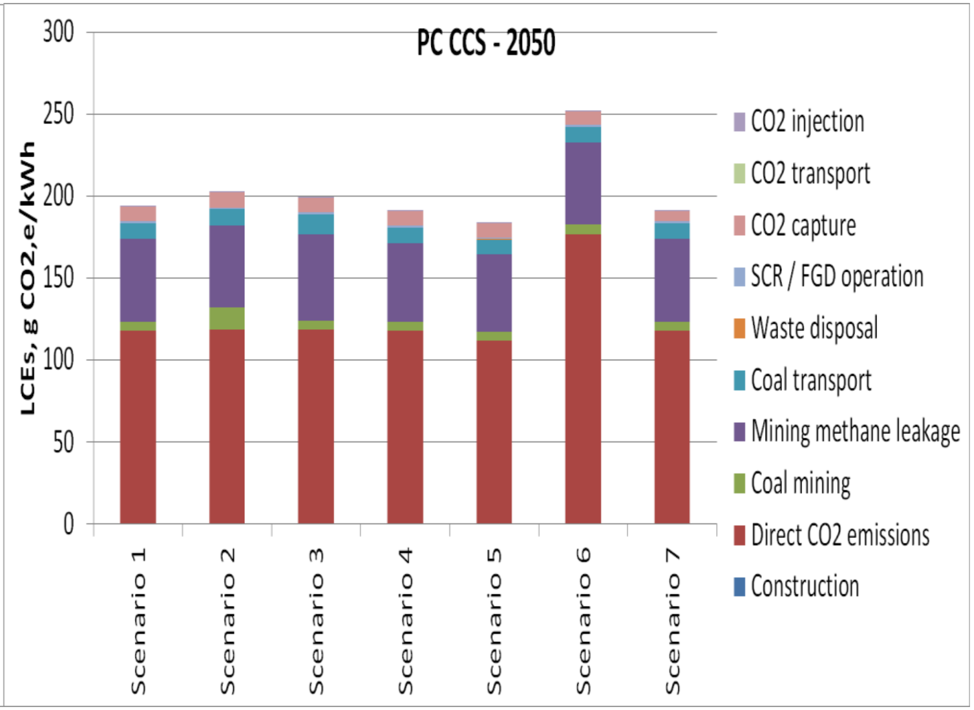
- The spreadsheet LCE calculation tool was run for the different scenarios. For each of the scenarios, all parameters are kept the same as in the base case except for the parameter being tested. The parameter being tested in each of the scenarios is applied for the whole period (current – 2050). The changes in LCEs with time are due to changes in carbon (both material and transport) and grid intensities. The results are shown below for PC with CCS.
- The highest effects on LCEs are observed for scenario 6 (reduction in capture efficiency to 85%). This increases LCEs by about 60 g/kWh. Reducing the CO_2 capture energy penalty by 20%reduces LCEs by 5-6%. Increasing coal imports from Russia by 15%, on the other hand is expected to increase LCEs by 2-4%.
- A 5% reduction in the methane leakage rate, leads to 2-3 g/kWh reduction in LCEs. While methane leakage is a major contributor to LCEs, reductions in methane leakage rates do not play a major role, as there are currently insufficient economic incentives for the capture of methane from coal mines. As a result a significant reduction in methane leakage rates is not expected.





Scenarios as described on slides 31-33

Sensitivity analysis: IGCC with CCS

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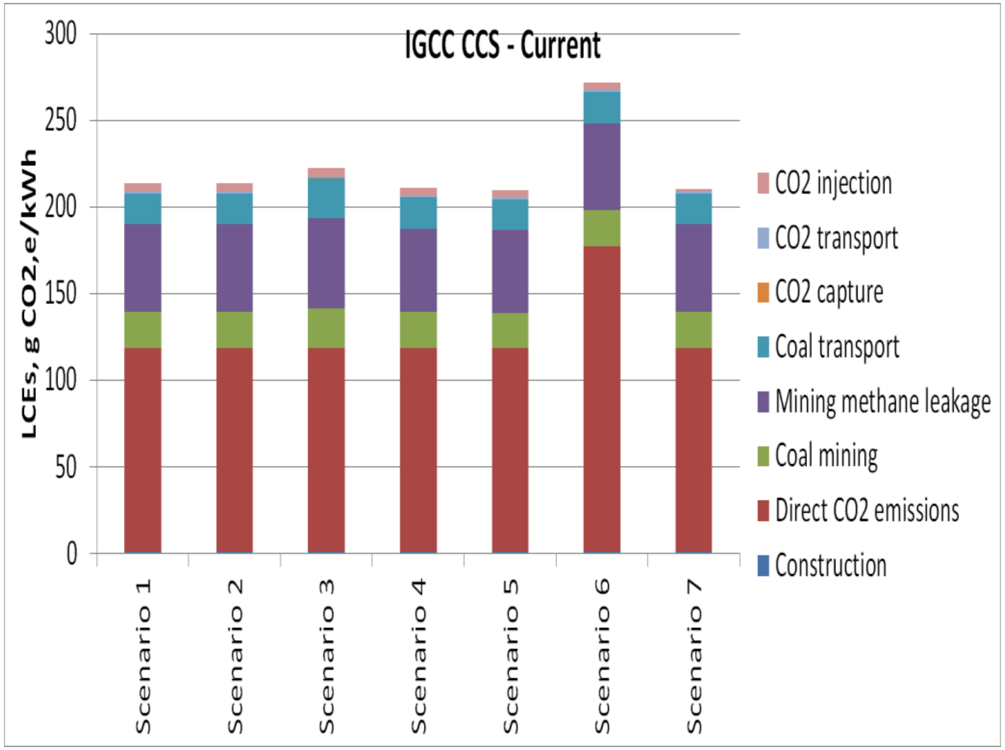
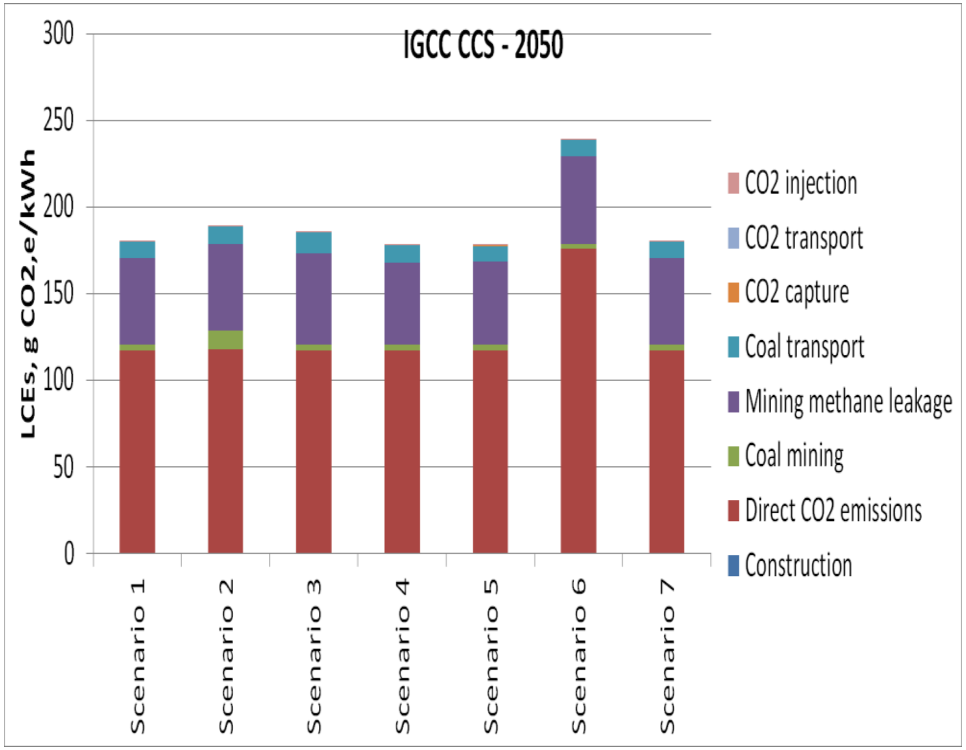
The different scenarios are compared for IGCC with CCS in the figure below. Once again, the reduction in the capture efficiency (from 90% to 85%) has the biggest effect on LCEs leading to a 27-32% increase. Scenario 7 (reduction in amine solvent consumption) is not relevant for IGCC. The consumption of the Selexol solvent for IGCC is negligible and so changes in solvent consumption for IGCC with pre-combustion capture is not expected to make a significant impact on LCEs.





Scenarios as described on slides 31-33

Conclusions: Coal CCS

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- Based on our analysis, for the base case scenario, the total life cycle emissions are around 220-290 g $CO_{2,e}$/kWh for PC with CCS and around 210 -270 g $CO_{2,e}$/kWh for IGCC with CCS. This is in agreement with figures reported by recent studies.
- Projected reductions in the carbon intensity of materials and electricity from the grid to 2050 is expected to reduce LCEs from coal CCS by 10-15%.
- For coal power plants without CCS, direct emissions represent more than 90% of total LCEs emissions. For power plants with 90% capture in the UK, the share of direct emissions to the total LCEs is expected to reduce to 45-55%.
- The main contributor to indirect emissions for coal CCS is mining operations including methane leakage from the mining site (which make up 60%-75% of all current indirect emissions, about 85% in 2050). While CO_2 capture-related emissions (those related to solvent and other chemical production) make up 3-4% of the total LCEs, CO_2 transport and storage emissions are negligible and are not expected to contribute significantly to LCEs.
- For the base scenario, about 60% of current total LCEs are UK-based. In 2050, UK-based emissions are in the range 55% to 70% of overall LCEs.
- The main factors influencing LCEs are the CO_2 capture efficiency, the capture plant energy consumption and the source of coal. Increasing the share of Russian coal by 15% could lead to a 2-4% increase in LCEs in 2050.
- Overall LCEs of the coal CCS life cycle can be reduced by abating emissions associated with mining. Methane leakage from deep coal mining can be reduced through methane capture, although this may require stimulation through additional policy interventions.
- Significant reductions in the LCEs can also be achieved through improvements in the capture plant (and in other environmental control processes such as FGD and SCR) energy consumption and through improvements in the CO_2 capture efficiency.

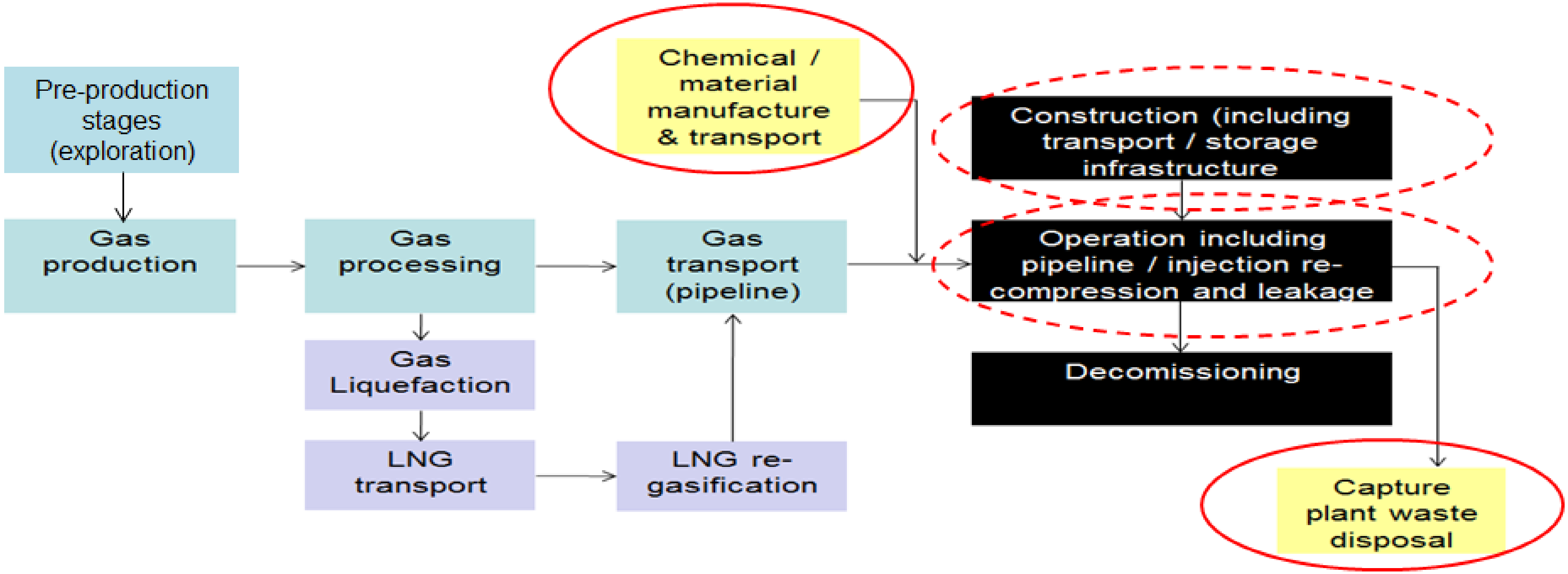
Gas with and without Carbon Capture and Storage (CCS)

The CCGT life cycle

RICARDO-AEA

This section discusses LCEs from CCGT both with and without CCS. The study covered both pipeline gas and LNG

- **The CCGT life cycle consists of three main stages: construction, operation and decommissioning.** The gas fuel cycle consists of gas production and processing, gas transport by pipeline in addition to gas combustion at the power plant. The processing stage is not discretely separate from the production in much of the literature. The inclusion of LNG in the fuel cycle adds three additional life cycle stages: gas liquefaction, LNG transport and LNG re-gasification
- **The addition of CCS** adds to the construction and decommissioning phases (the CO_2 pipeline transport and injection infrastructure) and to the operational phase (energy requirements for CO_2 capture, compression, transport and injection, chemical production and transport and waste disposal).



Red circles represent CCS-specific stages are: (1) chemical / material manufacture and transport, (2) capture plant waste disposal, (3) CO_2 capture plant construction and CO_2 transport / storage infrastructure, (4) operational emissions (i.e. capture plant energy requirements and transport pipeline re-compression requirements and injection site energy requirements).

Overall LCEs from CCGT (without CCS)

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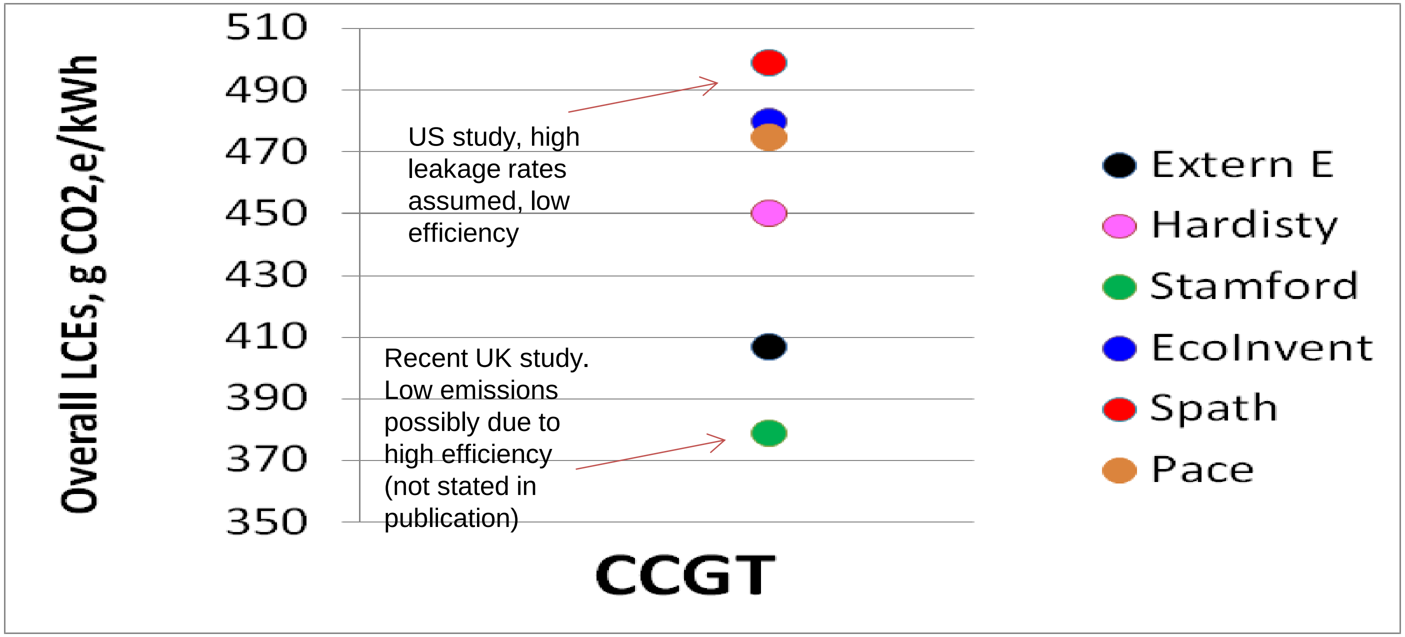
Previous studies on the LCEs associated with gas CCGT were reviewed. Earlier studies focussed on pipeline gas. More recent studies also consider LNG. The LCEs from selected studies are compared below.



- Total LCEs differ significantly depending on whether the study considers pipeline or LNG. LCEs from LNG are significantly higher due to the additional life cycle stages.
- The key factors influencing LCEs (for both pipeline and LNG) are (1) power plant efficiency, (2) methane leakage rate (methane has GWP of 21) during the different life cycle stages (processing, liquefaction, pipeline transport)
- Studies in the literature report a wide range for LCE emissions in the range 380-500 g $CO_{2,e}$/kWh.

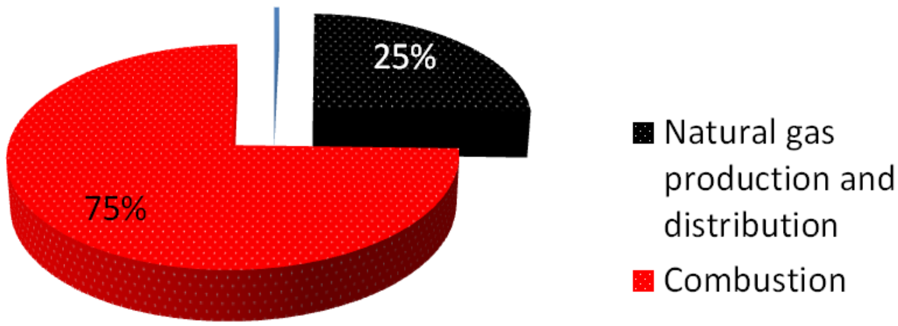
Some studies report LCEs as ‘per MJ or kWh of gas produced’ rather than ‘per kW of electricity produced’. For example, a study by Jaramillo (2009) reports overall LCEs from CCGT LNG of about 67 g $CO_{2,e}$/MJ of natural gas with 10-20% of emissions coming from the LNG life cycle stages. The power plant efficiency is not given for this study. Assuming CCGT power plant efficiency of 50%, this equates to about 480 g $CO_{2,e}$/kWh

	Extern E	EcoInvent	Stamford	Spath	Hardisty	Pace
Source of gas	UK	Various	UK	USA	Australia	US
Power plant location	UK	Switzerland	UK	USA	China	US
Gas type	**Pipeline**	**Pipeline**	**Pipeline**	**Pipeline**	**LNG**	**LNG**
Size, MWe	652	NA	1320-2000	505	NA	560
Efficiency	52% LHV	NA	NA	49% HHV	53%	51%
Load factor	90%	NA	63%	80%	NA	NA
Lifetime, years	30	NA	25	30	NA	NA

Breakdown of LCEs for CCGT without CCS

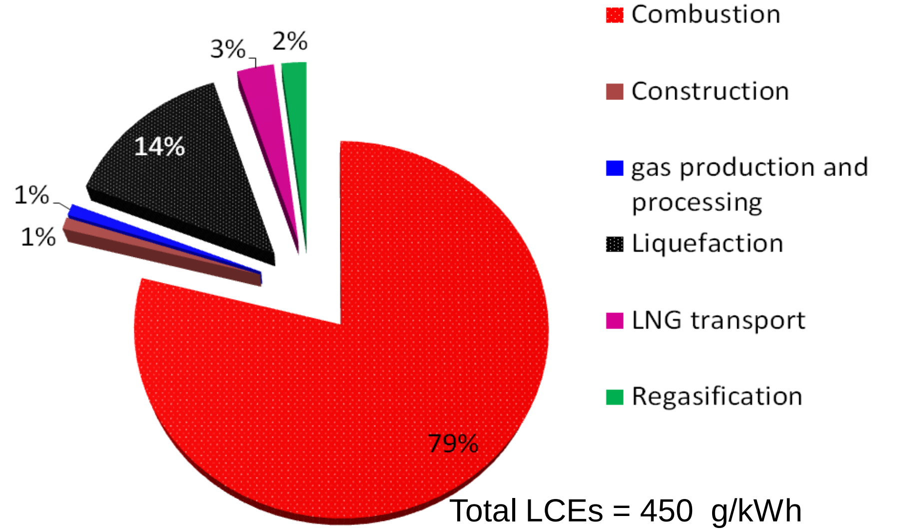
RICARDO-AEA

Spath, 2004



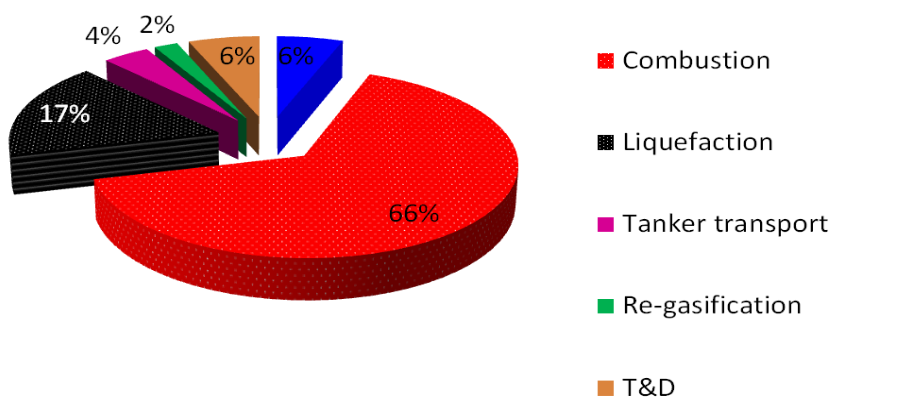
Total LCEs = 499 g/kWh

Hardisty, 2012



Total LCEs = 450 g/kWh

Jaramillo, 2009



- Combustion emissions represent the majority of LCEs. The study by Spath assumes high methane leakage rates (1.4%) and so the share of combustion emissions is lower.
- The addition of LNG is expected to lead to an increase in the share of upstream emissions due to liquefaction energy requirements

Emissions from the LNG life cycle

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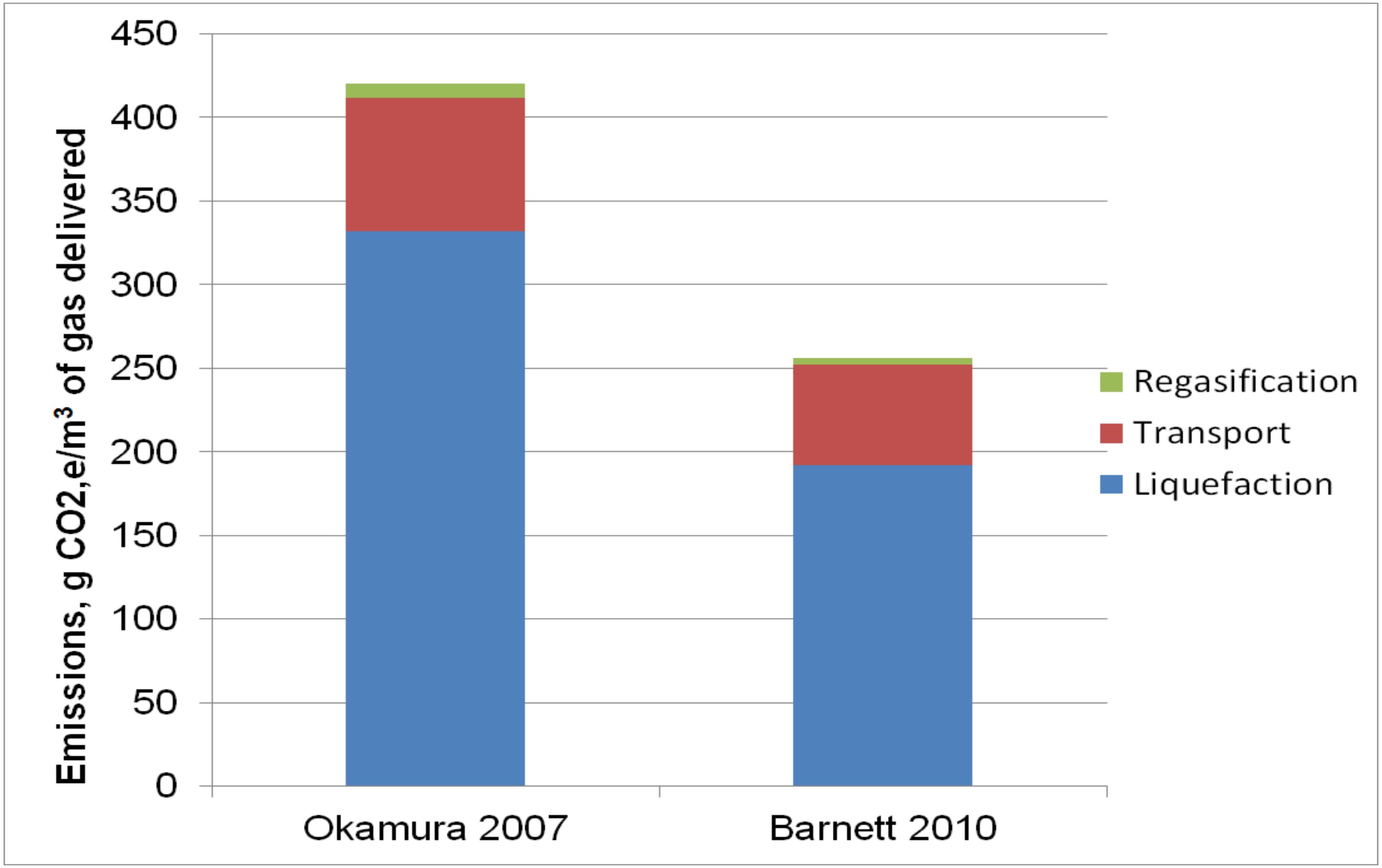
- For the gas LNG life cycle, the total LCEs from liquefaction, LNG transport and re-gasification are in the range 0.25 to 0.4 kg $CO_{2,e}/m^3$ LNG delivered as shown by the graph below based on Barnett (2010) and Okamura (2007). Figures reported by Conoco Phillips, Jaramillo (2009) and Tamura (2001) are also in the same range.
- Liquefaction is the main contributor to the LNG life cycle



LCEs from gas CCS

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- The life cycle stages covered by gas CCS are the same as for CCGT without CCS (i.e. including construction and decommissioning, gas pre-production stages, gas production / processing, methane leakage and compression along the gas transport pipeline, liquefaction, LNG transport, re-gasification). As shown in slide 38, the addition of CCS to CCGT adds additional life cycle stages.
- The life cycle stage parameters used in modelling LCEs from CCGT with CCS are the same as those used for CCGT without CCS. In addition, parameters for CO_2 capture (capture efficiency, energy penalty, solvent requirements), CO_2 transport (pipeline length, re-compression requirements) and CO_2 injection (e.g. type of aquifer) are also required.
- The literature was reviewed for studies giving estimates of LCEs for gas generation both with and without CCS. The next slide lists and compares recent studies. The table on the next slide shows the associated assumptions for each of the studies.
- The wide range reported for CCGT without CCS (and consequently from CCGT with CCS) is mainly attributed to variation in the assumed power plant efficiency. Net efficiencies considered for CCGT range from 48% to 60%. Different studies make varying assumptions of the energy penalty due to the addition of CCS on CCGT power plants (10-25% reduction in efficiency).
- Studies with high LCEs usually assume low power efficiency combined with high methane leakage rate assumptions.
- Most studies assume capture efficiency of 90%. Viebahn (2007) considered a capture efficiency of 88% for the amine capture process.
- Emissions from the construction and decommissioning life cycle stages are negligible and are sometimes excluded from the analysis.
- A comprehensive review of the literature on the LCA of CCS is given in the IEA report ‘Environmental evaluation of CCS using life cycle assessment’ (2010)

Overall LCEs from CCGT with CCS

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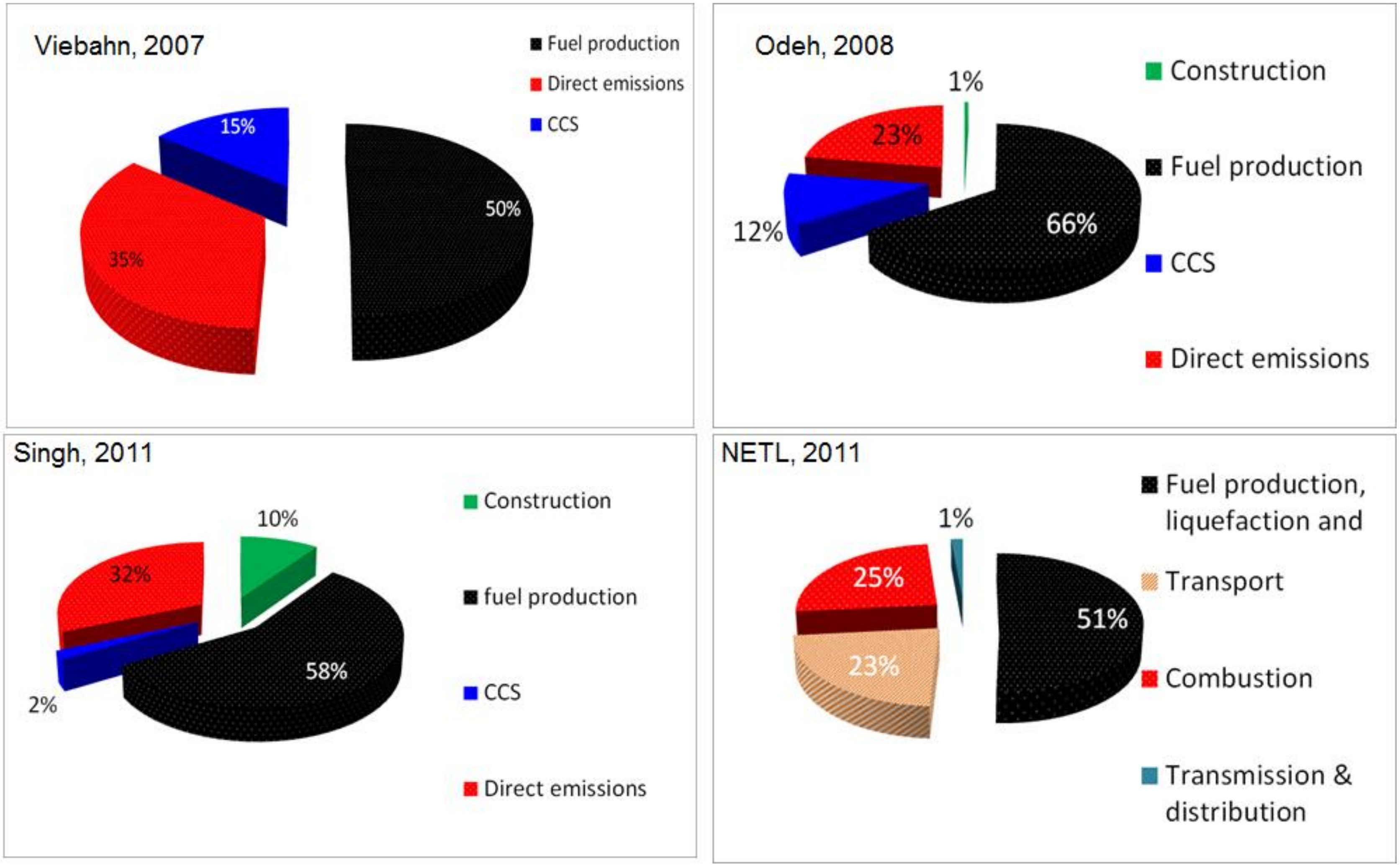
Studies in the literature usually compare CCGT with and without CCS as shown in the table below. LCEs for CCGT with CCS in the literature range from 90 to 245 g CO_2/kWh. This wide range is mainly attributed to different assumptions about the gas fuel cycle (e.g. methane leakage rates from transport pipeline, whether LNG is included) and technology parameters (e.g. the power plant efficiency, CO_2 capture efficiency and energy penalty).

Study	Year	Technology		Net capacity, MW	Net efficiency	Capture technology	CO_2 capture rate	LCEs, g CO_2,e/kWh	Comment
Spath	2004	CCGT	Pipeline	600	48.8%		-	499	Assumed high gas leakage rates
	2004	CCGT+ CCS		504	-	MEA	90%	245	
Viebahn	2007	CCGT	Pipeline	700	60%	Na	88%	396	
	2007	CCGT+ CCS		600	51%	MEA	88%	132	
Odeh	2008	CCGT	Pipeline	500	50.1%	Na	Na	488	Assumed high gas leakage rates and low power plant efficiency so high LCEs
	2008	CCGT+ CCS		432	43.8	MEA	90%	200	High leakage rates so upstream emissions are dominant
NEEDS	2008	CCGT	Pipeline	500	62%	-	-	366	
		CCGT+ CCS		-	56%	MEA	90%	93	
Modahl	2009	CCGT	Pipeline	832	59.1%	Na	na	395	
	2009	CCGT+ CCS		702	44.8%		90%	91	
NETL	2010	CCGT	Pipeline + LNG	-	-	Na		420	
		CCGT+ CCS		-	-	MEA	90%	203	Including LNG life cycle so high upstream emissions

Breakdown of LCEs for CCGT with CCS

RICARDO-AEA

Estimates of the breakdown of the LCEs by lifecycle stage, as reported in the literature, are shown below. It is noted that most LCEs arise from the fuel production stage (50-70%). These studies were selected for their availability of data.



LCEs from CCGT with and without CCS: comparison

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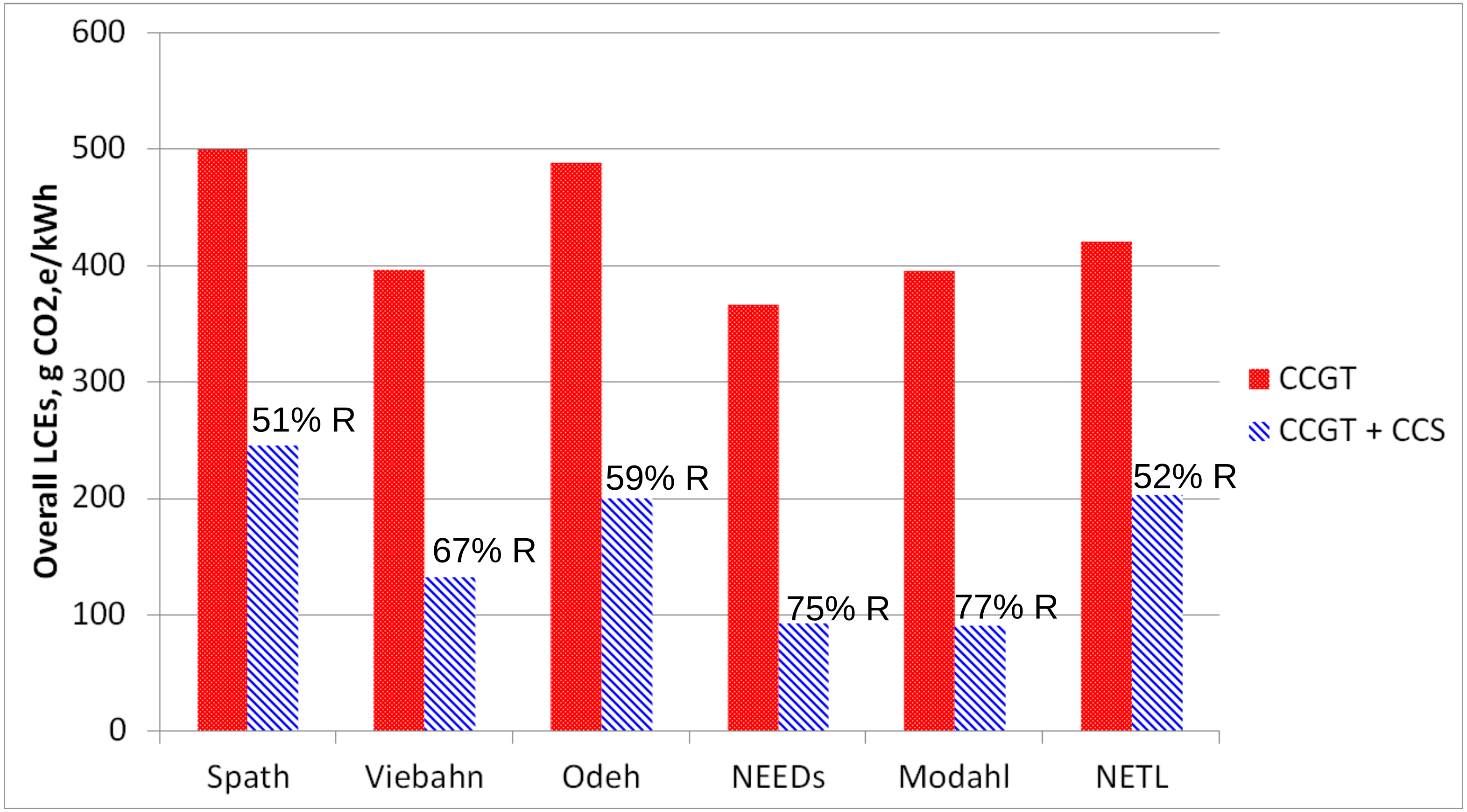

R = reduction relative to CCGT without CCS

The addition of CCS to CCGT leads to a reduction in overall LCEs in the range of 51-77%

Current emission hotspots in the gas CCS life cycle

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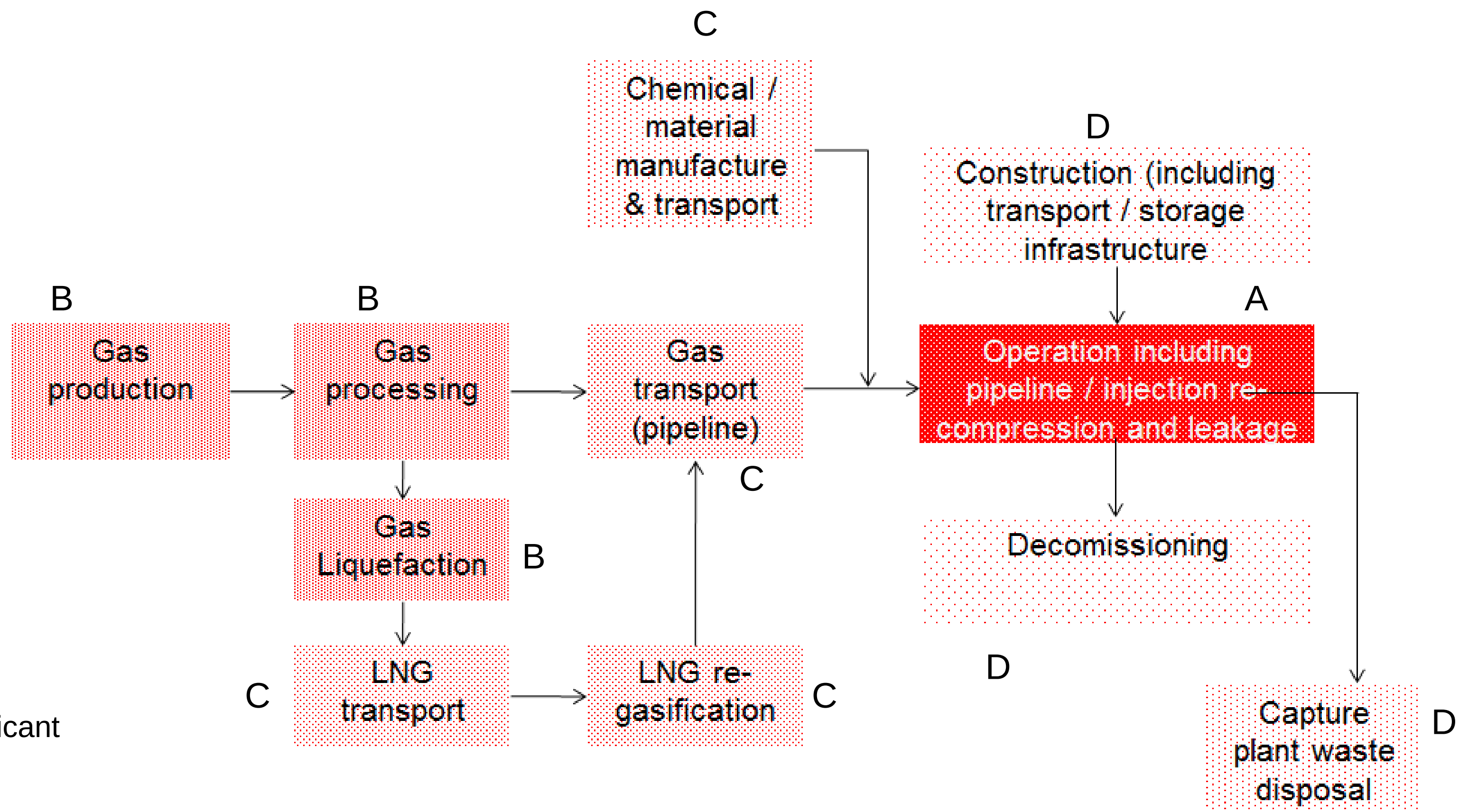
The hotspots for the CCGT life cycle with and without CCS are the same. Based upon the review of the literature, the key hotspots in the gas CCS life cycle i.e. the most important sources of LCEs, can be identified. These are shown below. Most emissions arise from combustion. Upstream emissions (production, processing, liquefaction, etc.) are significant and when added together become dominant. Construction, decommissioning and waste disposal emissions are relatively small.



A: Dominant
B: Significant
C: Less significant
D: Negligible

Geographical factors

- In the construction of the power plant, the main materials required for the power / capture plant and transport / storage infrastructure are concrete, steel, iron, aluminium and copper. For a UK power plant, these may either be sourced in the UK or internationally. Studies in the literature usually consider that raw materials are sourced locally within the country where the plant is constructed. Life cycle emissions from the construction phase are currently (and are expected to remain in the future) low in comparison to other LCEs and so the source of raw materials will have negligible effect on overall LCEs.

- Other than combustion, the main contributor to LCEs is gas production and processing including (in case of LNG) liquefaction. The location where gas is produced will have an effect due to specific leakage rates and energy consumption during production.

- Currently, about 50% of natural gas used in the UK is imported. Of the imported gas, 46% is LNG (85% from Qatar, 5% Nigeria, 4% Norway and 6% other). Pipeline gas is imported from Norway (76%), the Netherlands (22%) and Russia through Belgium (2%).

- It can be assumed that combustion and construction emissions are UK emissions while all other upstream fuel emissions are non-UK emissions.

- Energy requirements for the transport pipeline and storage site will depend on whether the CO_2 is stored in the UK or overseas. This study assumes that all CO_2 will be stored in the UK and so all transport / storage emissions will be UK emissions.

- The UK has strong chemical industry and so it is expected that the chemicals required for the capture plant and other processes will be manufactured in the UK.

Base cases scenario: Power plant data

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In our base case scenario, the assumed characteristics of the power plant are shown in the tables below. Data for the power plant was obtained from Parson Brinkerhoff (2012).

Parameter	CCGT	CCGT + CCS
Capacity (MW)	900	780
Load factor (%)	85%	85%
Net power efficiency*	59%	51%
Lifetime (years)	30	30
CO_2 capture rate	NA	90%

* Energy consumption by the CO_2 capture process and other processes with in the power plant are already accounted for

Data on energy requirements, flaring and methane leakage (diffuse emissions) for the gas production and processing and gas liquefaction stages were obtained from a report by AEA (2012) on the climate impacts of shale gas production. These are reported for different countries including Norway, the Netherlands, Russia and the Middle East. Weighted averages for energy consumption and methane leakage during the different stages were estimated based on the share of imported gas, share of LNG and share of different countries in the imported gas mix. **See table on next slides (under gas fuel cycle parameters) for estimated values.**

Assumptions were also made about the LNG transport and regasifiaction emission factors (based on Centre for Liquefied Natural Gas, 2009), and transport pipeline energy requirements and methane leakage (based on AEA's shale gas report) as shown below.

Parameter	
Transport emission factor, kg $CO_{2,e}/m^3$ LNG	0.0055
Regasification emission factor, kg $CO_{2,e}/m^3$ LNG	0.013
Methane leakage rate (pipeline), % of throughput	0.03%
Gas compression requirements (pipeline), % of throughput	1.80%

Base case scenario assumptions summary

RICARDO-AEA

Details of the base case (applicable for both CCGT and CCGT with CCS) are shown in the table below.

Parameter	Base scenario assumption
Power plant parameters	As listed on previous slide.
Raw material carbon intensity	Base – based on the IEA 2 degrees scenario
Grid intensity	Base – based on the IEA 2 degrees scenario
Source of gas	The base scenario assumes 50% of gas is imported. Of the imported gas, 46% is LNG (85% Qatar, 5% Nigeria, 4% Norway and 6% other, average). The pipeline imports are assumed 76% from Norway, 22% from the Netherlands and 2% from Belgium.
Gas fuel cycle parameters	Pre-production methane leakage: 0.2% (weighted average) Gas production emissions factor (EF): 0.043 kg CO_2/m^3 (weighted average) Pipeline methane leakage: 0.03% per 1000 km (weighted average) pipeline compression energy requirements: 1.8% per 1000 km (weighted average) Pipeline distance: 545 km (weighted average) Liquefaction EF: 0.246 kg CO_2/m^3 of gas liquefied (weighted average) LNG transport EF: 0.0055 kg CO_2/m^3 of LNG (weighted average) LNG transport distance: 10,862 km (weighted average) Regasification EF: 0.013 kg CO_2/m^3 of gas send out (weighted average)
Capture plant	Chemical absorption via MEA, 2.34 kg MEA/t CO_2 captured. 90 % capture rate.
CO_2 transport	By pipeline, 300 km (100 km onshore), leakage rate of 0.026% per 1000 km is assumed.
CO_2 storage	Injection in gas fields

Comparison with previous studies: CCGT

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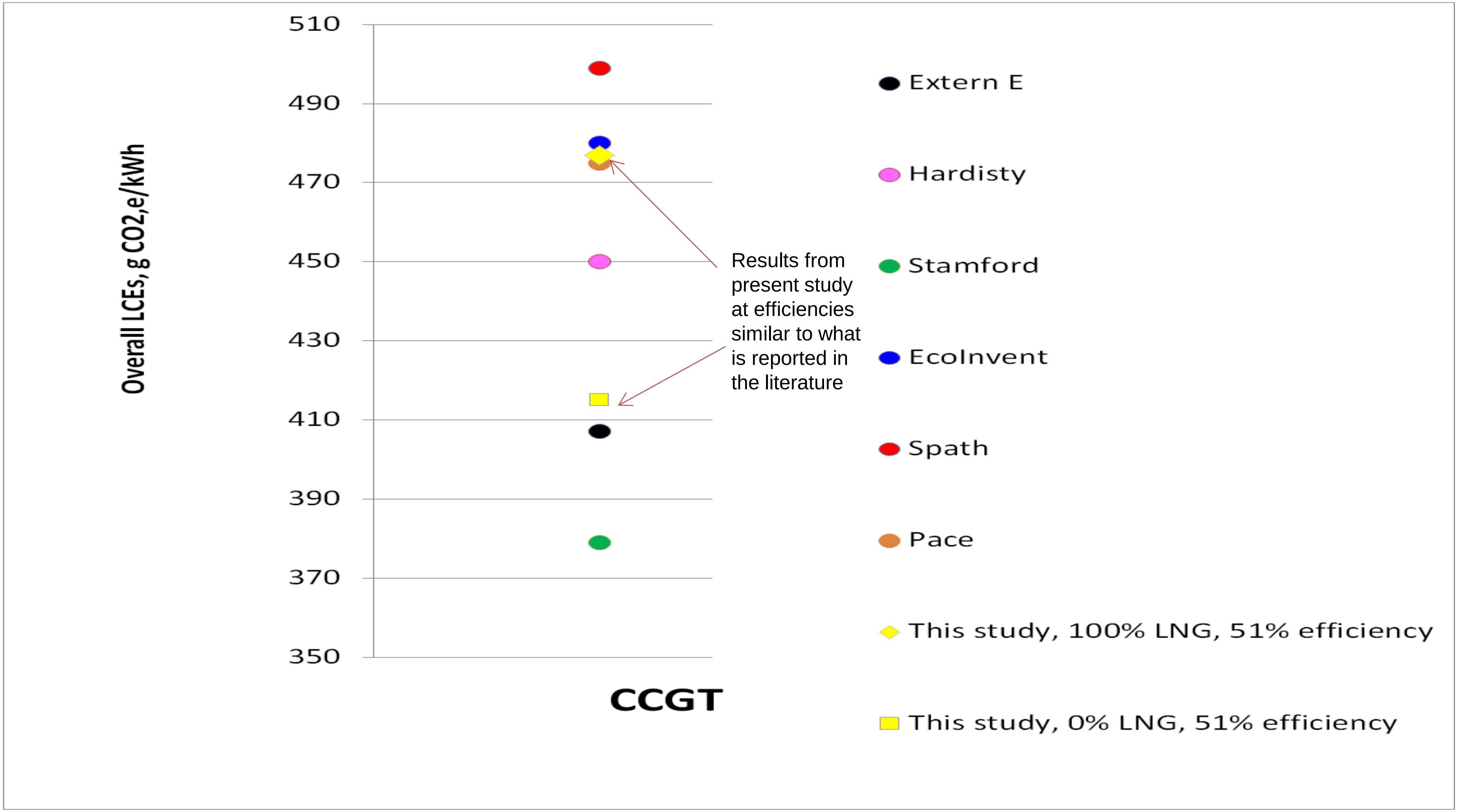
The studies compared below cover both LNG and pipeline studies. Results from this study, normalised to 51% efficiency (average from recent studies) are compared to the literature assuming 100% LNG and 0% LNG. For the base scenario, total LCEs for CCGT are 376 g $CO_{2,e}$/kWh. For the current UK gas mix, LCEs are 410 g $CO_{2,e}$/kWh at 51% efficiency and 355 g CO2/kWh at 59% efficiency.



Comparison with previous studies: CCGT + CCS

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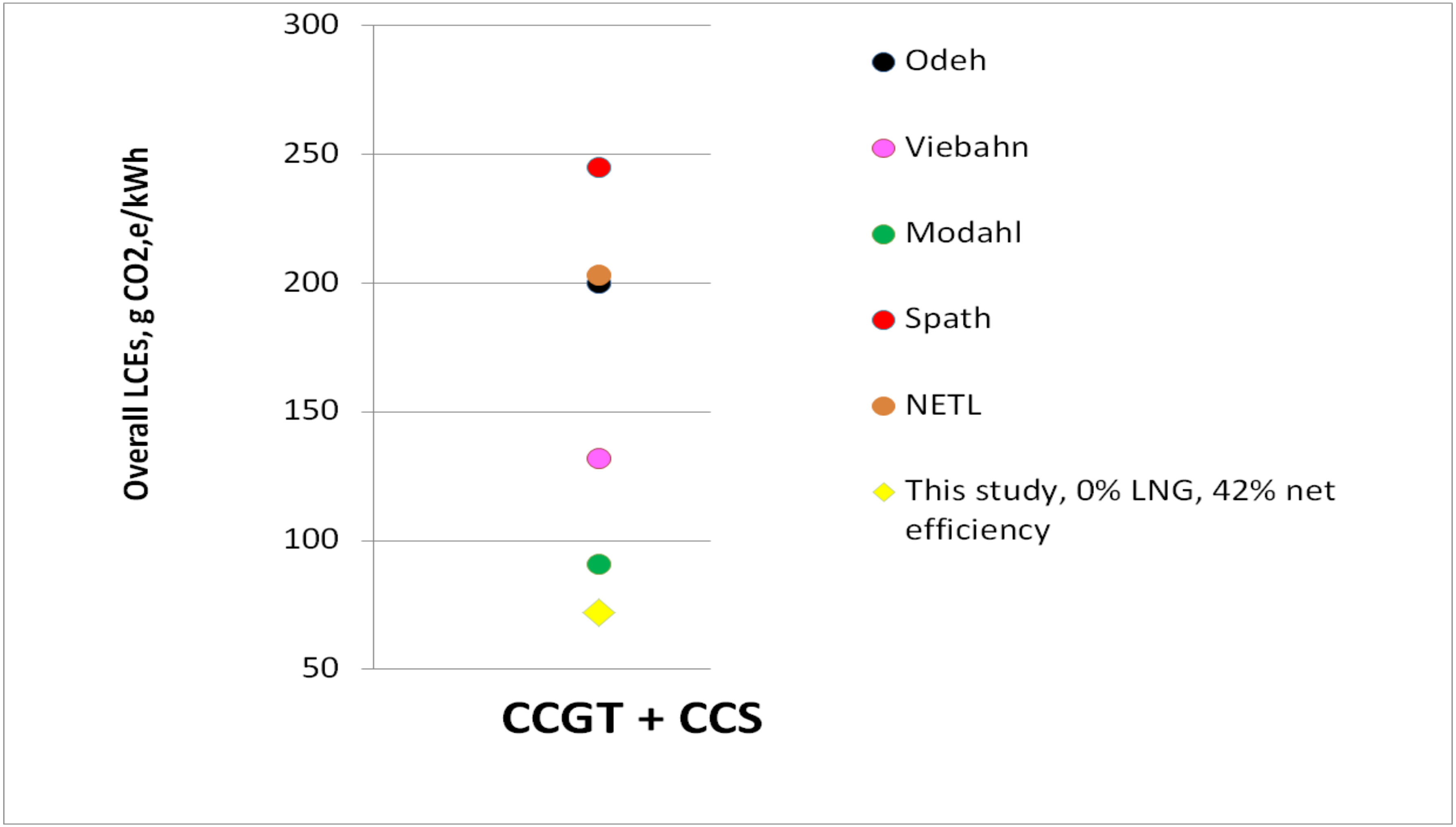
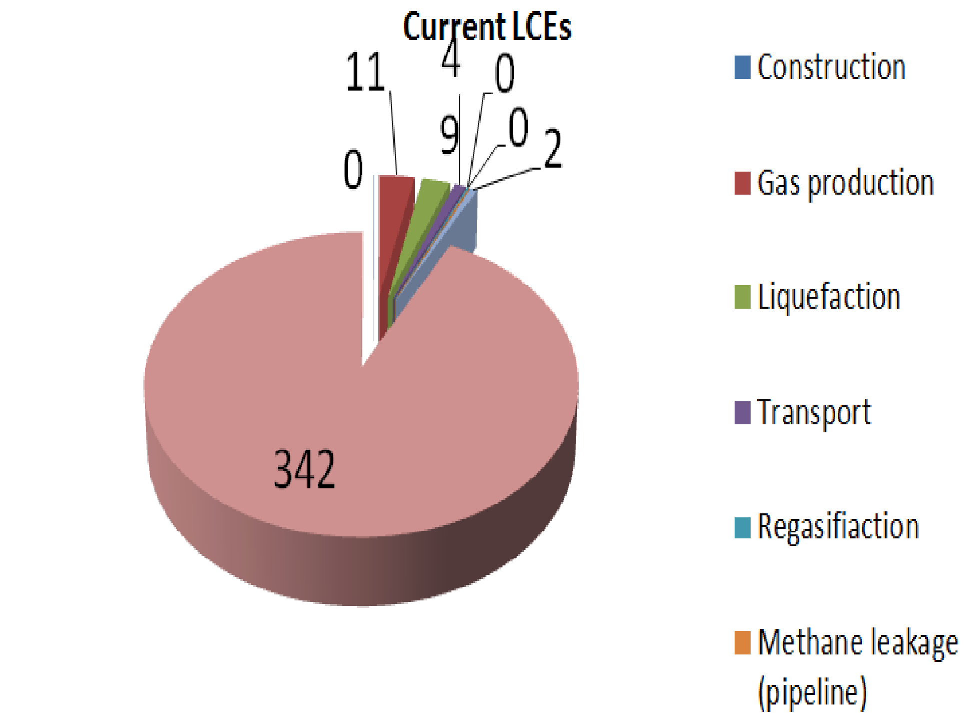
The studies compared below only cover gas pipeline (no LNG studies). Results from this study are normalised to 42% net efficiency and compared to other studies below. The result obtained from this study is lower than figures reported in the literature as a result of the lower leakage rates assumptions.



Base scenario: current LCEs

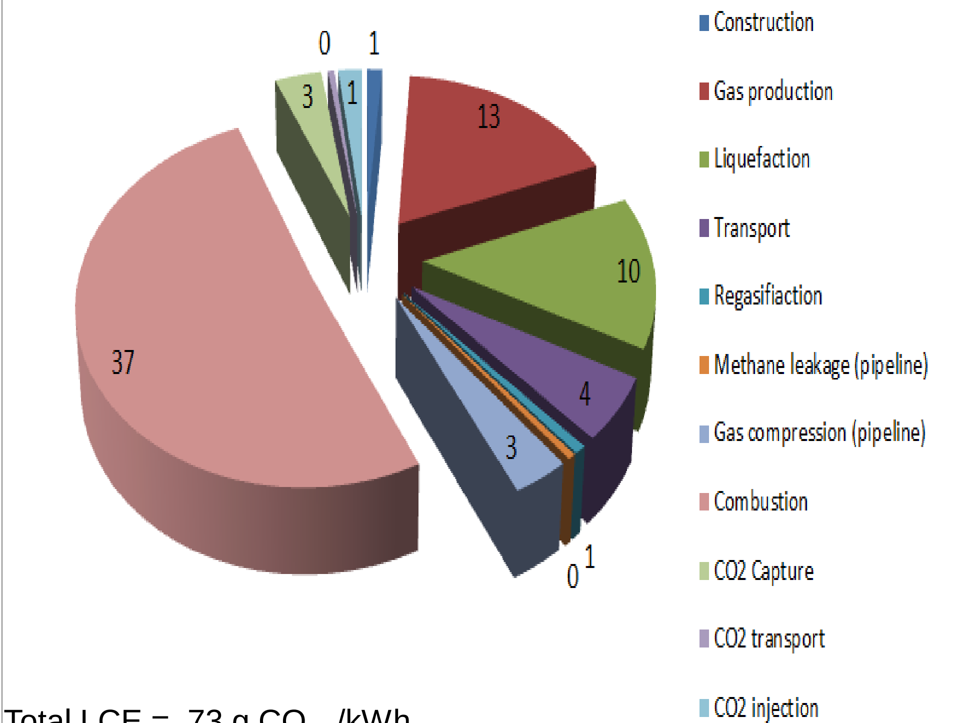
RICARDO-AEA

CCGT without CCS, g $CO_{2,e}$/kWh



Total LCE = 369 g $CO_{2,e}$/kWh

CCGT with CCS, g $CO_{2,e}$/kWh



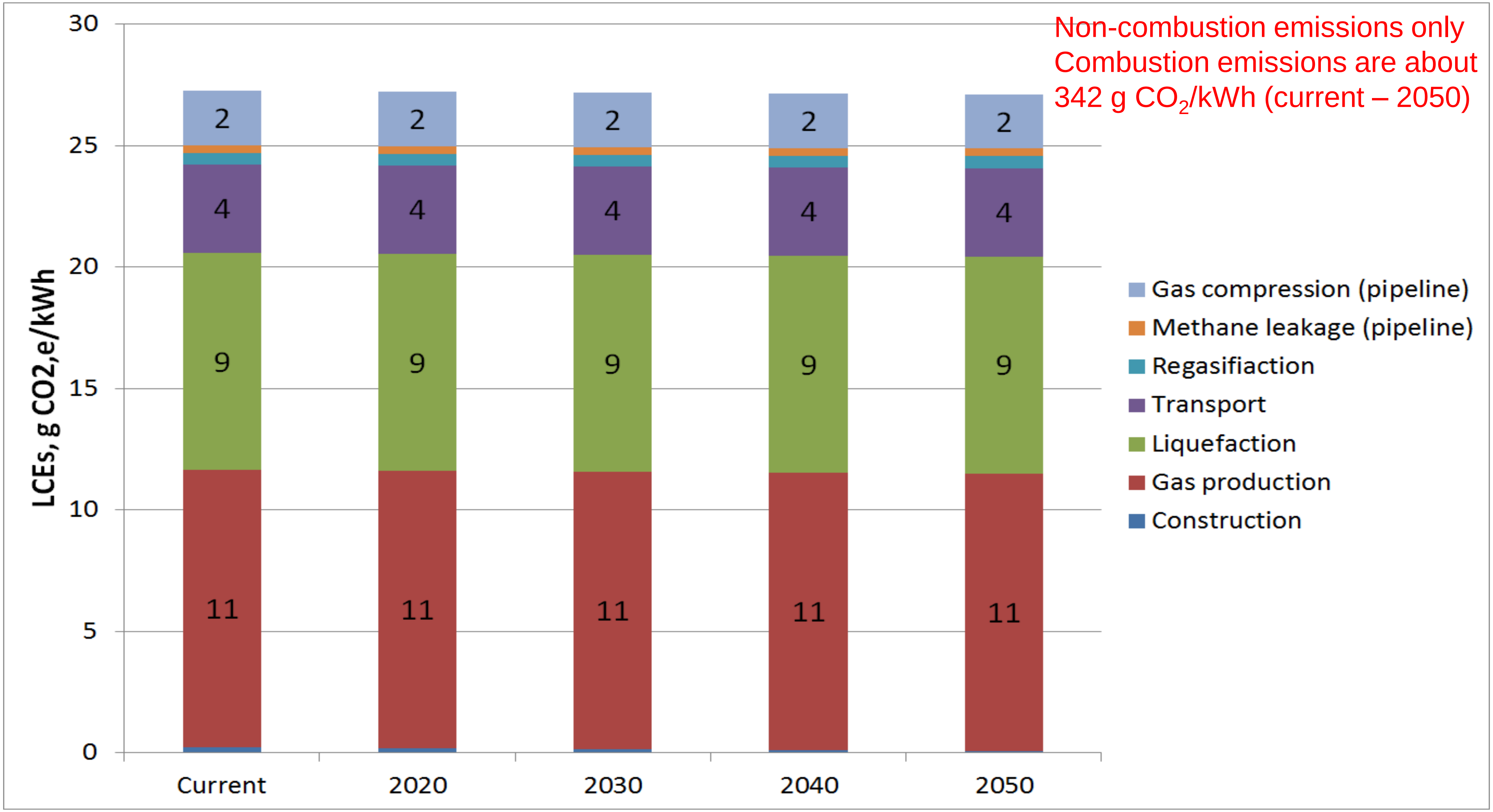
Total LCE = 73 g $CO_{2,e}$/kWh

- The addition of CCS, reduces LCE by 80% (for 90% capture) from 369 to 73 g $CO_{2,e}$/kWh.
- The share of combustion emissions reduces from about 90% to 50%.
- Other than combustion emissions, gas production and liquefaction emissions contribute the most to total LCEs. For CCGT without CCS, gas production and liquefaction emissions together make up 5% of total LCEs while for CCGT with CCS, these two make up more than 30% of total LCEs.
- CCS-related emissions are insignificant contributing only about 5% to total LCEs for CCGT with CCS.

CCGT without CCS: Base scenario

RICARDO-AEA

LCEs remain relatively constant to 2050. For the base scenario (46% of imported gas is LNG), LCEs from gas production and gas liquefaction (assuming gas-driven) remain the main contributors to 2050.



CCGT with CCS: Base scenario

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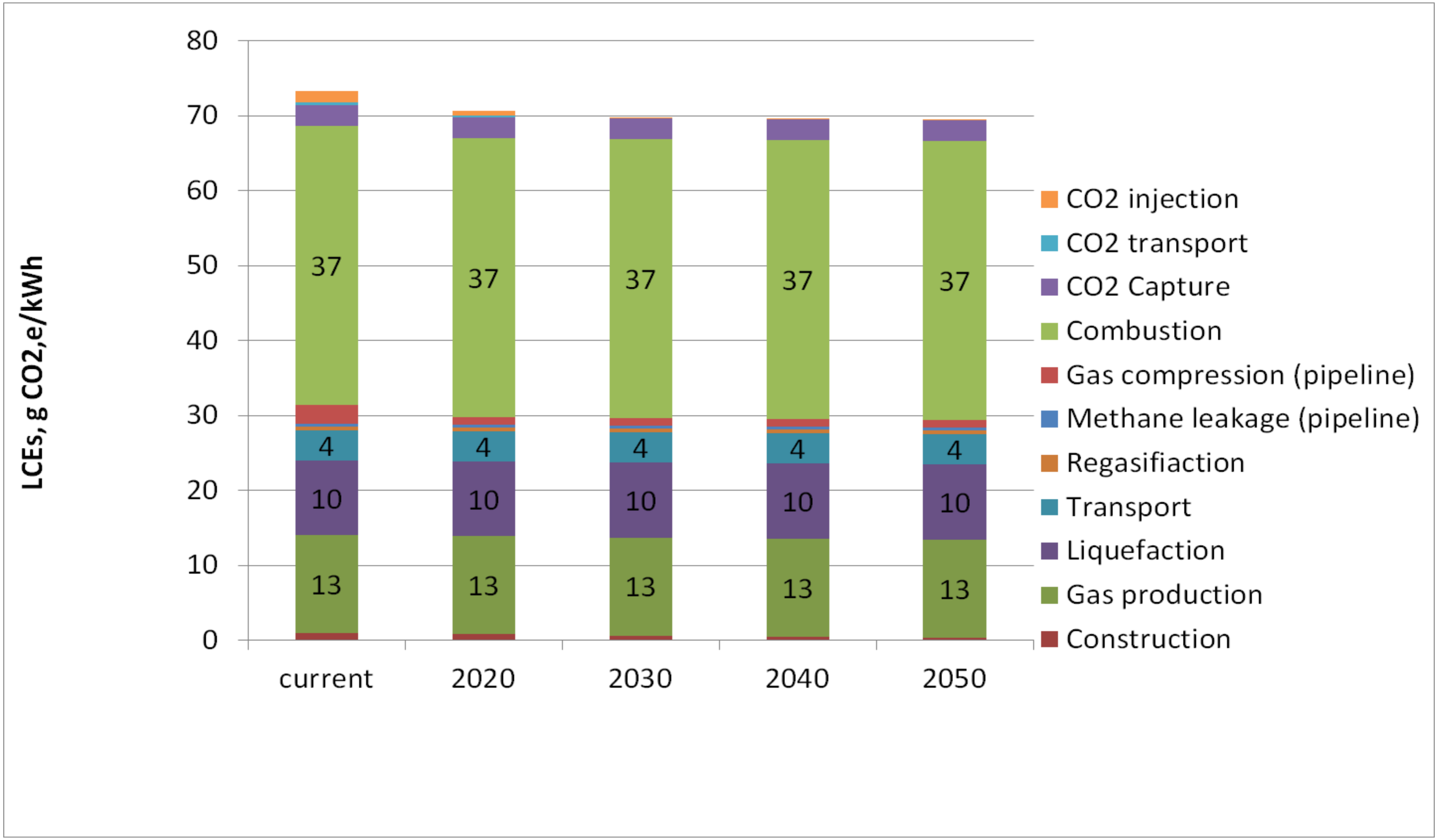
LCEs remain relatively constant to 2050. For the base scenario (46% LNG), LCEs from liquefaction (assuming gas-driven) remain the main contributor to 2050. CO_2 transport and injection LCEs reduce with time as the grid is decarbonised. Construction LCEs also reduce over time due to reduction in material carbon intensity.



Location of emissions: base scenario

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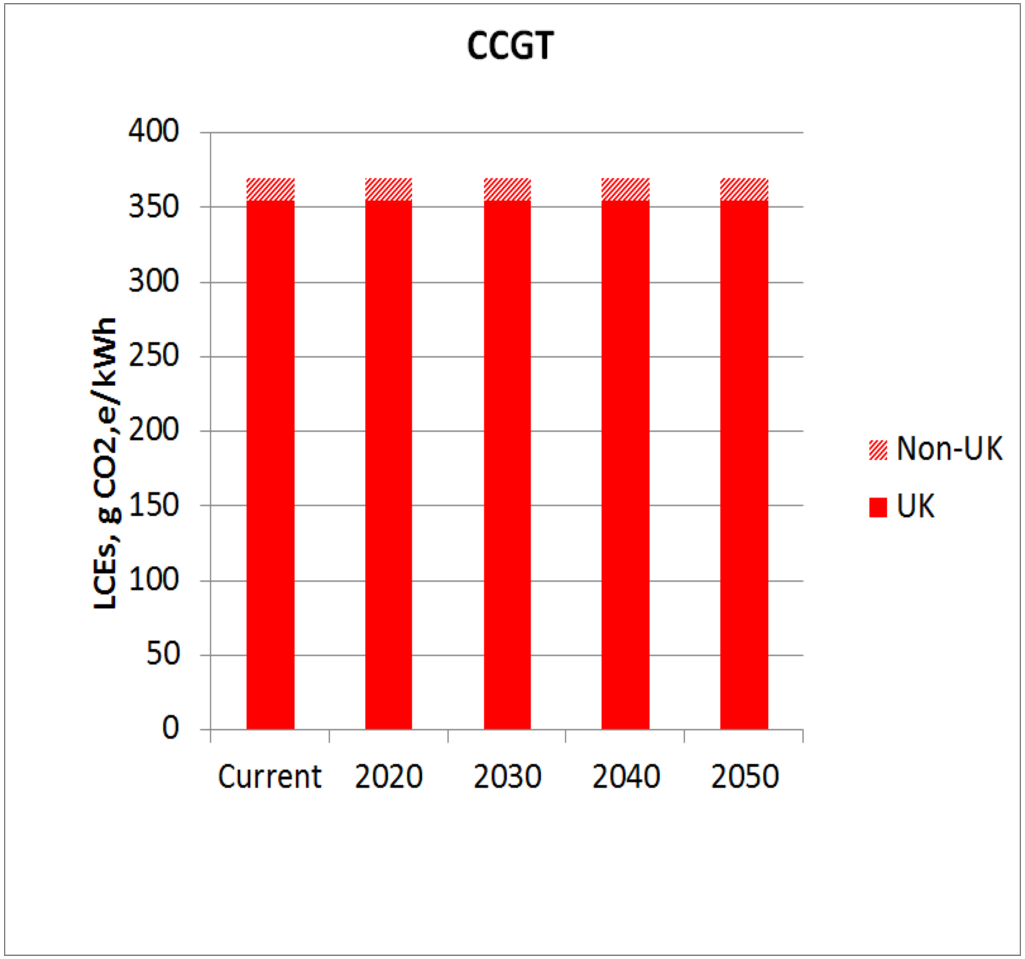
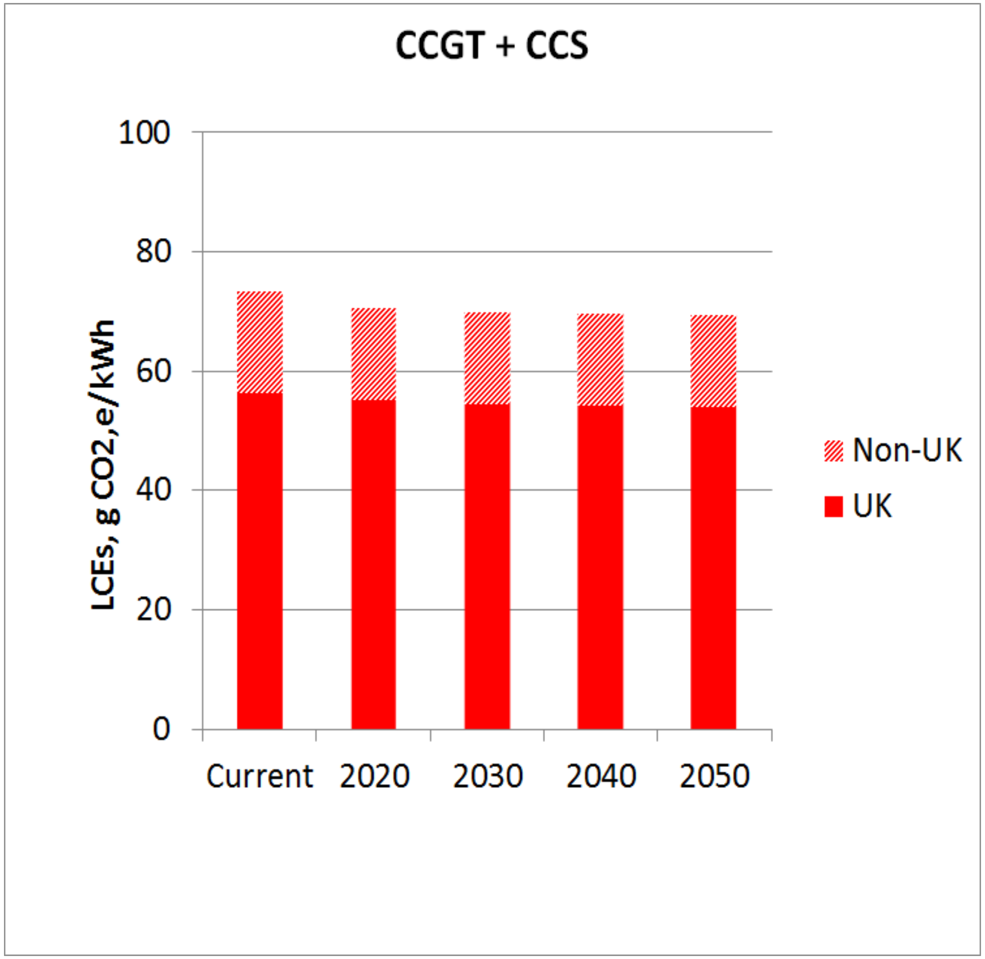




- The addition of CCS to CCGT power plants leads to a significant reduction in direct emissions and thus leading to a shift in the UK/non-UK LCEs split.

Sensitivity analysis (CCGT without CCS)

RICARDO-AEA

Scenario	Parameter tested	Description
Scenario 1: Base	As described above	
Scenario 2	Power plant efficiency	55% power efficiency instead of 59%
Scenario 3	Methane leakage rate	Assuming higher methane leakage rate (assuming leakage rate for pipeline from Russia, 0.23%)
Scenario 4	% of imported gas	Assuming that all gas (100%) is imported, maintaining the current pipeline-LNG mix
Scenario 5	Method of liquefaction	Assuming liquefaction by electricity As the grid becomes decarbonised in the future, liquefaction could become electricity- rather than gas-driven.
Scenario 6	Share of LNG in the imported gas mix	Currently, 46% of UK gas comes from LNG and this is expected to increase in the future. This scenario assumes 100% LNG.
Scenario 7	Share of gas-by-pipeline in the imported gas mix	This scenario assumes no LNG.
Scenario 8	Shale gas scenario	This scenario assumes 2% pre-production methane leakage and 0% flaring. Shale gas is associated with higher pre-production leakage rates in comparison to conventional gas

Sensitivity analysis results

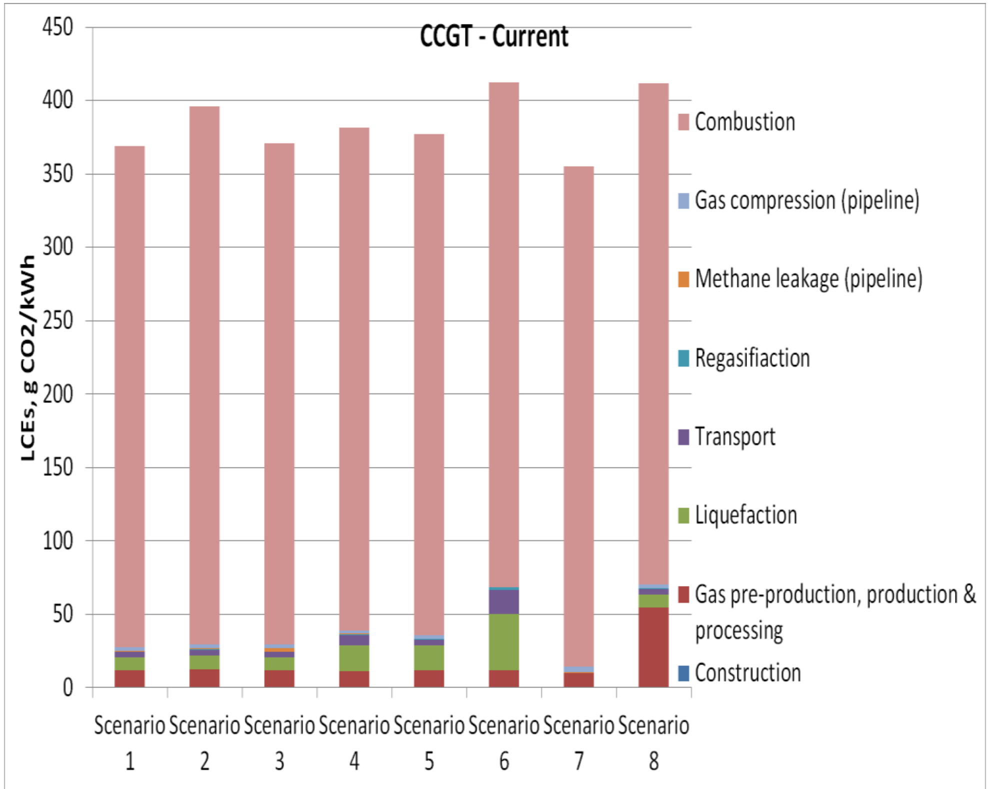
RICARDO-AEA

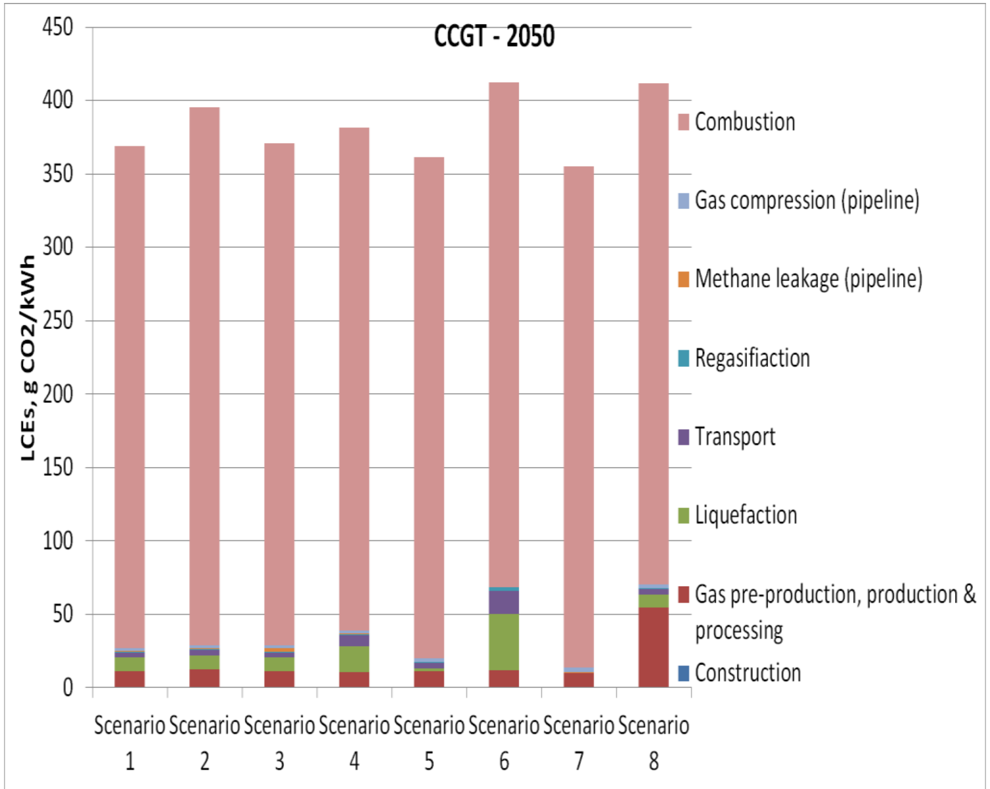
Results for the different scenarios are shown below. The key factors influencing LCEs are

- the power plant efficiency: a reduction of efficiency from 59% to 55% increase LCEs by 7%.
- share of LNG in the imported gas (Scenario 6: 100% LNG increase LCEs by about 10% relative to the base scenario). If none of the imported gas is from LNG (Scenario 7, assuming 100% import, 0% LNG), LCEs are reduced by 4%.

- The method of liquefaction (Scenario 5): 100% electricity-based liquefaction leads to slightly higher LCEs currently in 2020 in comparison to the base scenario (where gas-driven liquefaction is assumed). Beyond 2030, electricity-driven liquefaction gives lower LCEs (lower by about 2% in 2050)

In a scenario where pre-production emissions are increased to 2% (relevant to shale gas), LCEs increase by about 10%.





Scenarios as described on slide 56

Sensitivity analysis (CCGT with CCS)

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Scenario	Parameter tested	
Scenario 1: Base	As described above	
Scenario 2	Reduction of capture efficiency to 85%	Base scenario assumption is 90%. Applied on a large scale, the technology may not perform as anticipated. NER300 sets a threshold of 85% so this will be tested.
Scenario 3	Consumption of MEA solvent is reduced from 2.34 kg/t CO_2 captured to 1.6 kg/t CO_2	Effort is underway to reduce consumption of amine solvents. The IPCC Special report on CCS (2005) reports a figure of 1.6 kg amine / t CO_2
Scenario 4	Injection and storage of CO_2 in a saline aquifer instead of a gas field	Gas fields as well as saline aquifers are potential candidates for CO_2 storage. Initially, storage will most likely be in oil and gas fields.
Scenario 5	Liquefaction by electricity	As the grid becomes decarbonised in the future, liquefaction could become electricity- rather than gas-driven.
Scenario 6	Increase share of imported gas from LNG to 100%	Currently, 46% of UK gas comes from LNG and this is expected to increase in the future.
Scenario 7	Reduce share of gas from LNG to 0%	
Scenario 8	Shale gas scenario assuming 2% pre-production methane leakage and 0% flaring	Shale gas is associated with higher pre-production leakage rates in comparison to conventional gas

Sensitivity analysis results

RICARDO-AEA

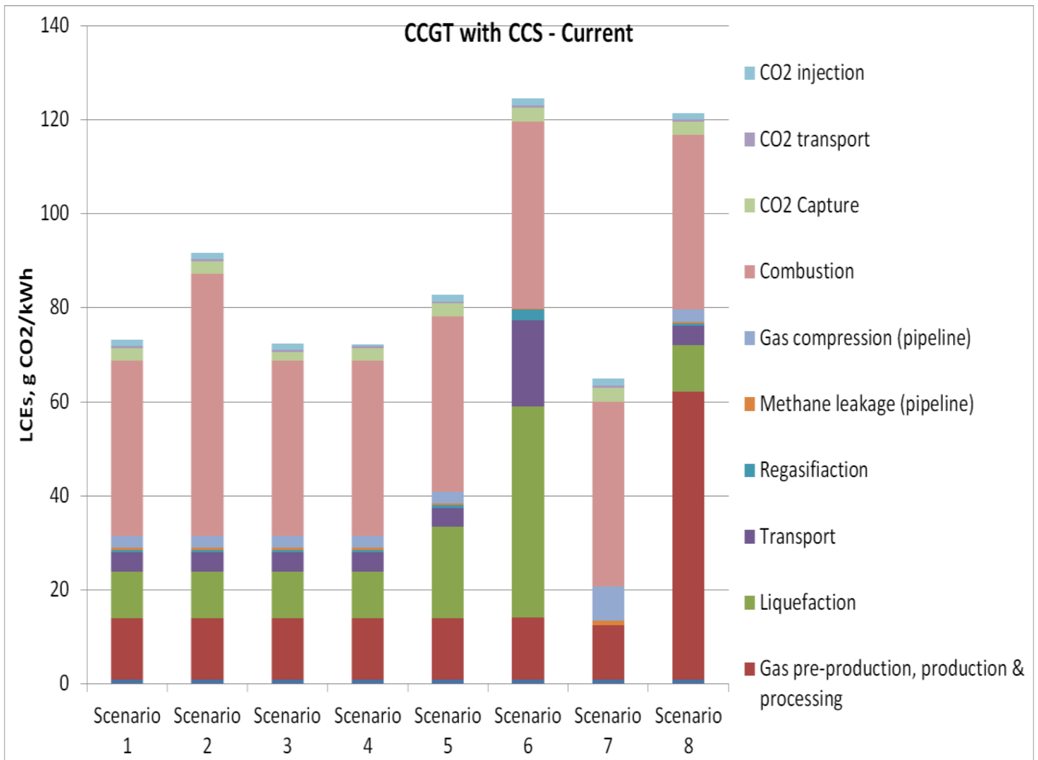
Results for the different scenarios are shown below. While the solvent consumption (kg / kg CO_2 captured) and the type of storage site (aquifer vs gas field) have minimal effect on LCEs, a reduction in capture efficiency (from 90% to 85%) increases LCEs by about 25%.

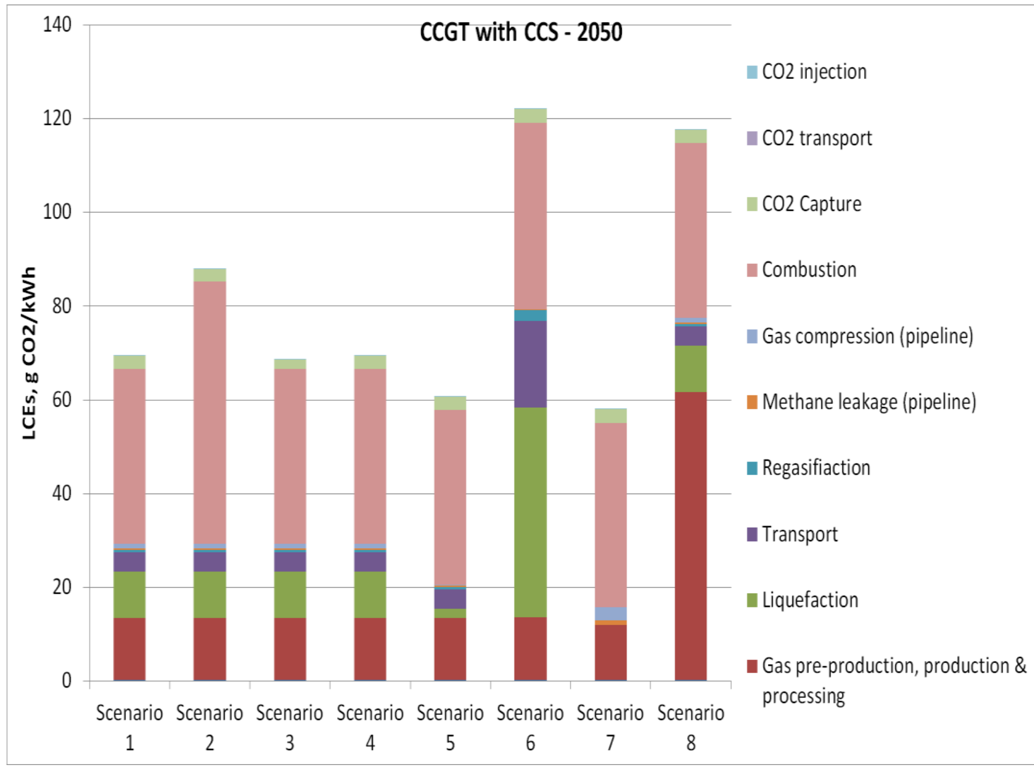
As for CCGT, the key factors influencing LCEs are:

- the share of LNG in the imported gas (100% LNG increase LCEs by 70-75% relative to the base scenario). If none of the imported gas is from LNG (assuming 100% import), LCEs are reduced by10-15%.
- The method of liquefaction (Scenario 5): 100% electricity-based liquefaction leads to higher LCEs currently and in 2020 in comparison to the base scenario (where gas-driven liquefaction is assumed). Beyond 2030, electricity-driven liquefaction produces lower LCEs (lower by about 13% in 2050)

Also, in a scenario where pre-production emissions are increased to 2% (relevant to shale rather than conventional gas), LCEs increase by 65-70%.

It is seen that with the addition of CCS to CCGT, each of the parameters tested has a higher weight than for the power plant without CCS.





Scenarios as described on slide 58

Conclusions: Gas CCS

RICARDO-AEA

- Based on our analysis, LCEs are 369 - 412 g $CO_{2,e}$/kWh for CCGT and 73 - 124 g $CO_{2,e}$/kWh for CCGT with CCS. Direct emissions represent more than 90% of total LCEs for CCGT and about 45-50% for CCGT with CCS (for 90% capture).

- The main contributor to indirect emissions is gas production and processing and gas liquefaction followed by LNG transport and CO_2 capture. CO_2 transport and injection (assuming storage in gas fields or aquifers) do not contribute significantly to LCEs. Methane leakage from gas pipeline, gas compression requirements along the pipeline and LNG re-gasification do not contribute significantly to LCEs.

- Currently most LCEs from CCGT are UK-based emissions. However, for CCGT with CCS, as CO_2 is captured, most emissions will become non-UK based emissions.

- The key factor influencing future LCEs is the share of LNG in the gas mix. In a scenario where all gas used the power plant is from LNG, LCEs from the base scenario will increase by 10% for CCGT without CCS and by 90-75% for CCGT with CCS.

- Currently, liquefaction is mostly gas-driven. If current systems are replaced by electricity-driven liquefaction systems, higher LCEs will result currently and in 2020. However, as the grid is decarbonised, this option will yield lower LCEs starting in 2030.

- Increasing pre-production methane leakage from 0.2% to 2% (relevant for the shale gas life cycle), increases LCEs by 10% for CCGT without CCS and by 65-70% for CCGT with CCS.

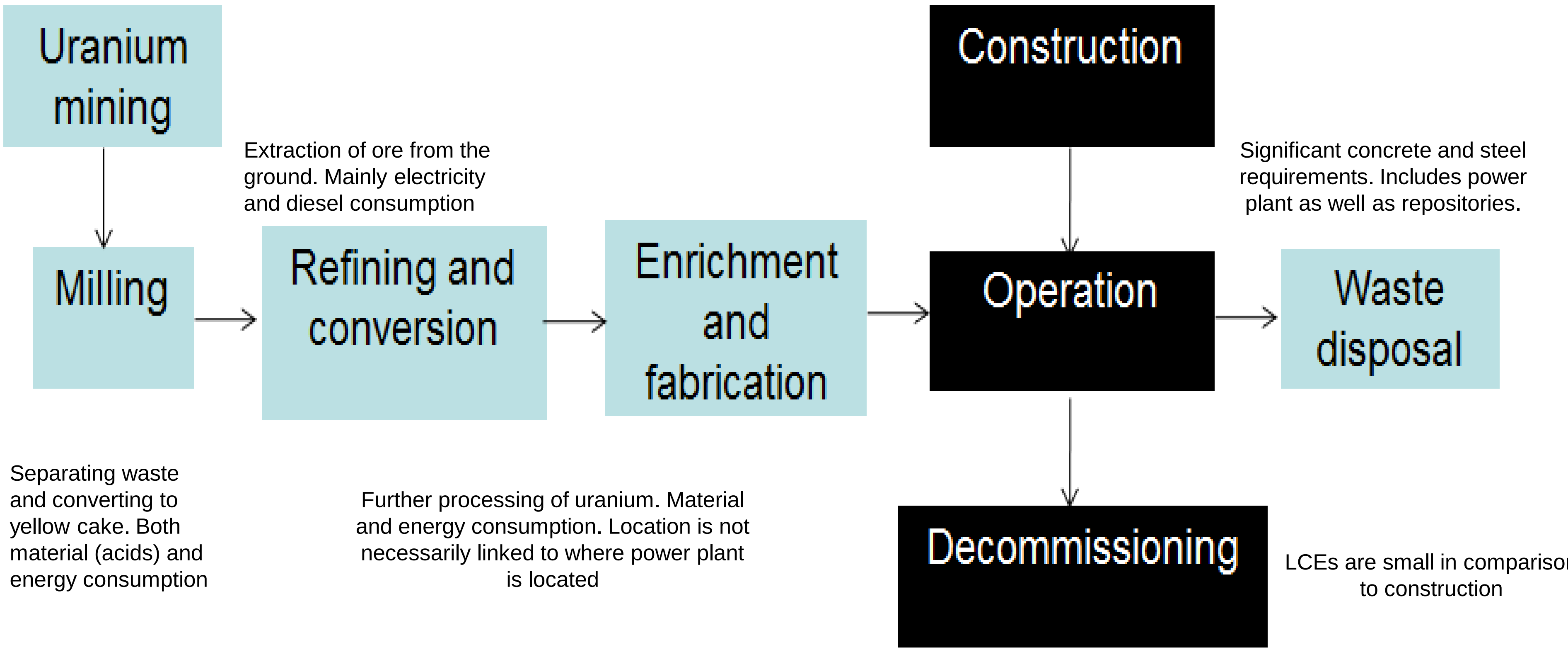
- In terms of CCS-related factors, the biggest impact on LCEs can be caused by a reduction in capture efficiency from 90% to 85%. This is expected to increase current LCEs by about 25%.

The nuclear life cycle

The nuclear life cycle

RICARDO-AEA

Current and future LCEs were estimated for pressurised water reactor (PWR) nuclear power plants. Similar to fossil fuel plants, the nuclear life cycle consists of three main stages: construction, operation and decommissioning. The uranium fuel cycle consists of mining, milling, refining, conversion, enrichment and fabrication. Since nuclear power generation produces radioactive waste, the waste disposal stage is more important that for other technologies. The construction covers both the power plant and repositories where waste is stored.



The lifecycle shown above represents a open fuel cycle, which assumed the use of virgin ores rather than reprocessing and re-use of uranium as part of a closed cycle.

Overall LCE emissions (range in the literature)

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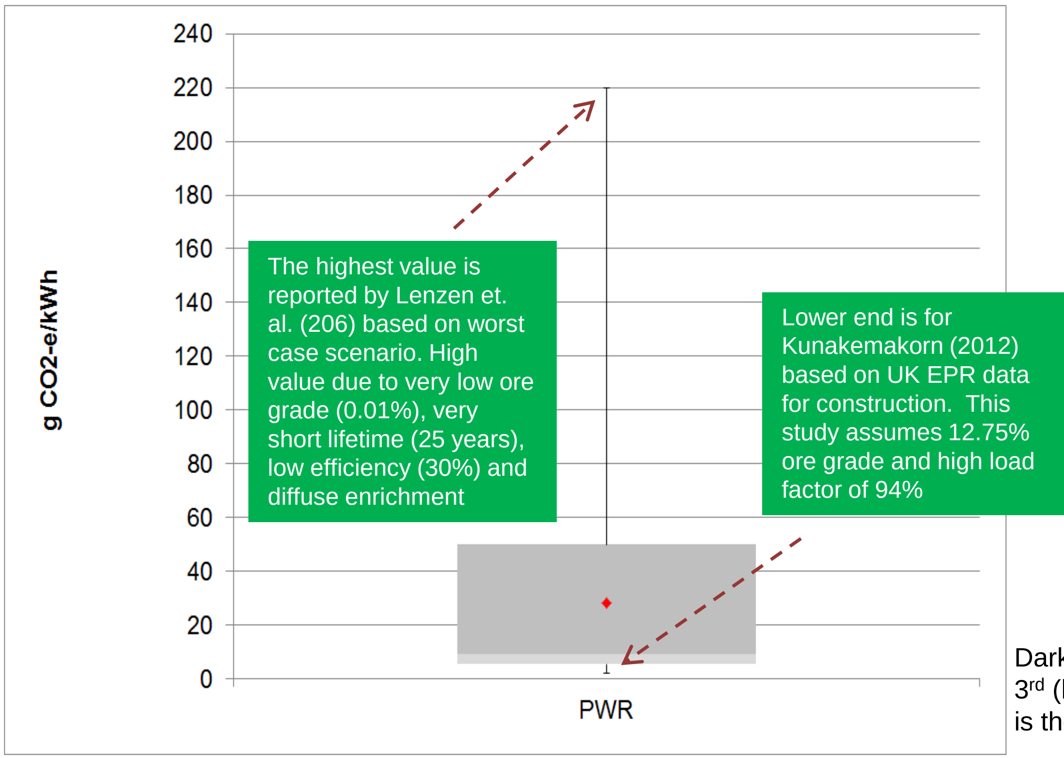
❑ The literature on nuclear fuel cycle has been reviewed for the pressurised water reactor (PWR). A wide variation is observed in the reported overall LCEs. Earlier studies in general reported very high LCEs. Later studies, on the other hand, report lower LCEs since higher plant efficiencies, longer lifetimes and less material requirements are usually assumed.

❑ The main parameters influencing LCEs are (1) uranium ore grade, (2) power plant capacity factor, efficiency and lifetime, (3) enrichment method and (4) type of uranium mine. Assumptions on these parameters are shown on the next slide.



Dark grey box: 1st (upper) quartile, Lighter grey box: 3rd (lower) quartile, separating line between two boxes is the median, red diamond: mean

Most data points (59) are obtained from the Journal of Industrial Ecology (2012). Additional European and UK studies (next slide) are also included. In addition, a recent study by Kunakemakorn (2012), which is lowest in the range, is also included.

It can be seen from the figure that the majority of estimates fall below 30 $gCO_{2,\,e}$/kWh, though the outliers indicate that footprints can be higher.

Range of assumptions in the literature

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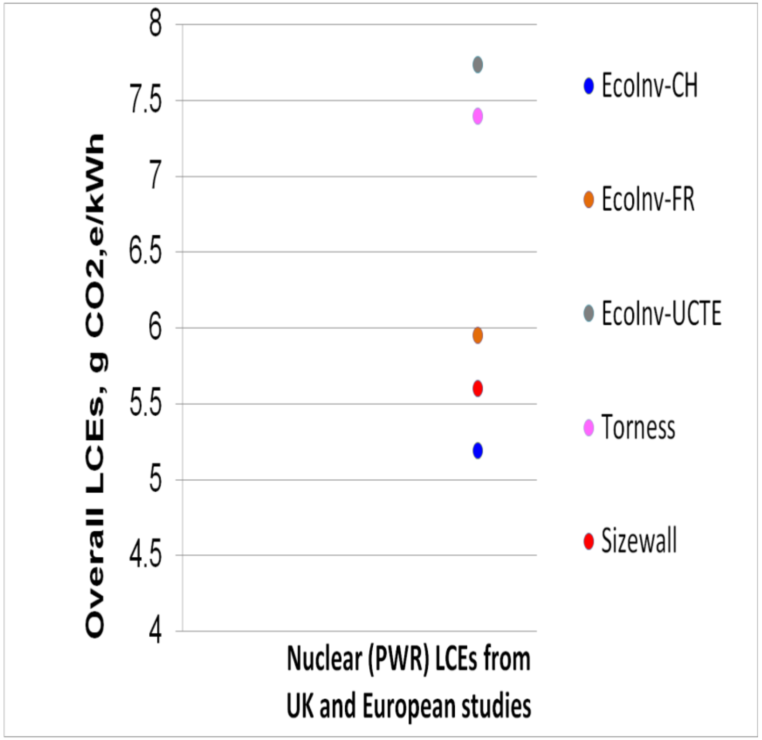
The literature reports a wide range for nuclear LCEs with the majority of studies (worldwide) reporting LCEs below 30 g $CO_{2,e}$/kWh. Several European studies report LCEs in the range 5- 8 g $CO_{2,e}$/ kWh as shown in the figure below. UK and European studies assume high power plant efficiency and comparatively lower emissions from construction and mining and milling emissions.

The range of assumptions for the studies used in constructing the graph in the previous slide are shown in the table. It can be seen from this table that here is a wide range of assumptions used in the literature. This, as a result, leads to a wide range of LCEs.

Difference in methodology are also important. For example, some studies use expenditure data and input-output analysis to calculate the construction related emissions, whereas others estimate impacts based on the volume of material (e.g. steel, concrete) consumed.



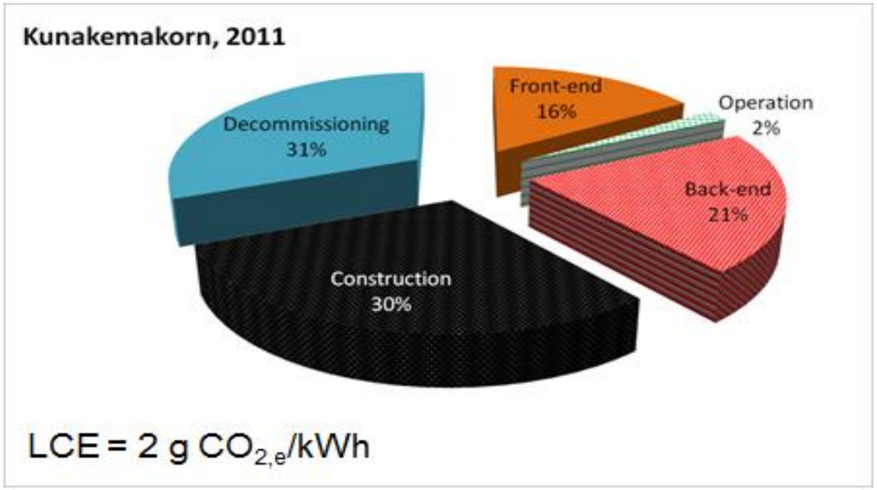
Year of study	1989 – 2012
Location	Finland, US, UK, Australia, Germany, Japan, Sweden, Belgium, Thailand
Capacity, MW	1000 – 3671
Lifetime	30 – 60 years
Capacity factor	70% – 94%
Efficiency	30 – 36%
Uranium ore grade	0.01 – 12.9% (highest Kunakemakorn, lowest: Lenzen)
Mining method	Open cast, underground or mix
Enrichment method	Diffusion, centrifuge or mix

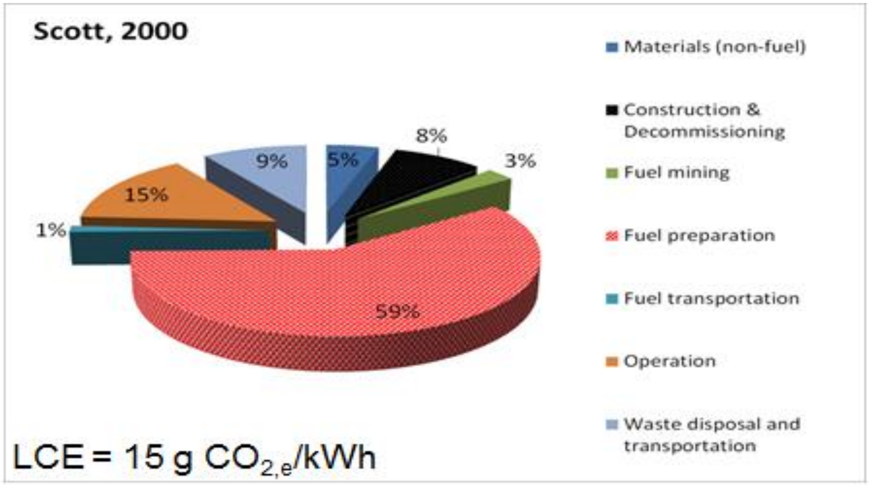
Breakdown of life cycle emissions

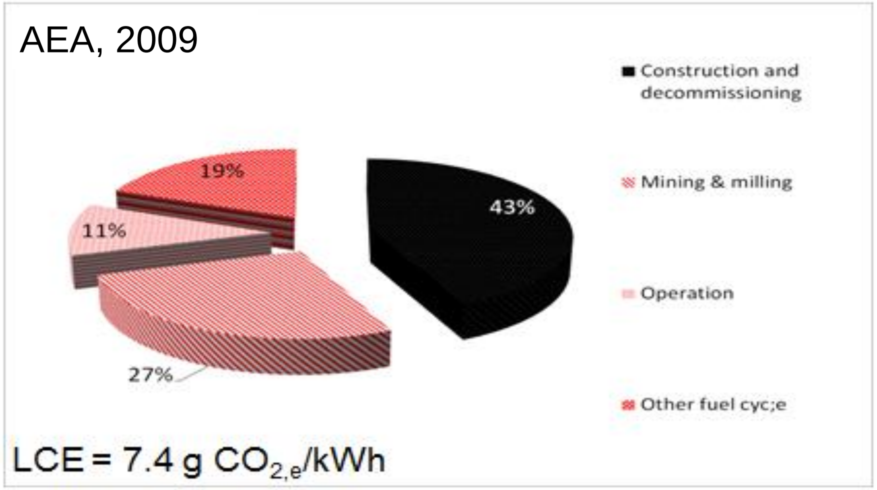
RICARDO-AEA

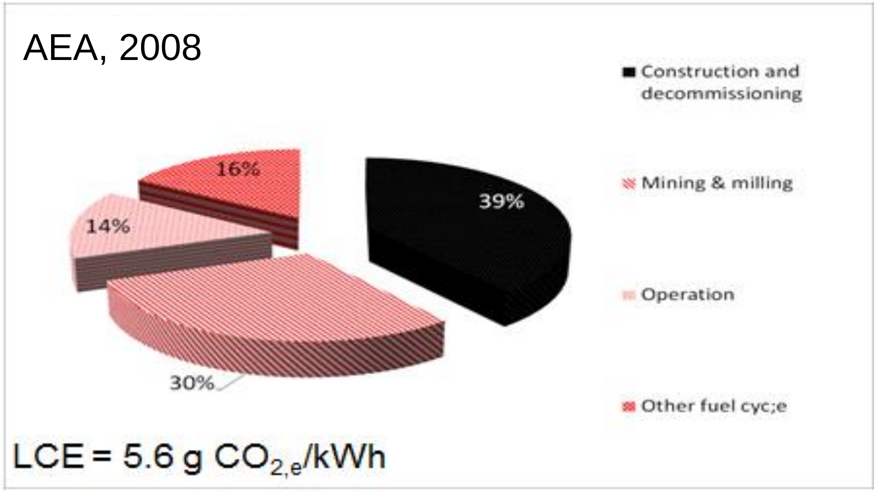
Estimates of the breakdown of the LCEs by lifecycle stage, as reported in the literature, are shown below. These studies were selected for their availability of data and consistency in the breakdown of the LCEs.

The construction phase and fuel production phases (mainly mining and milling) are the main contributors to LCEs.









Current emission hotspots in the nuclear life cycle

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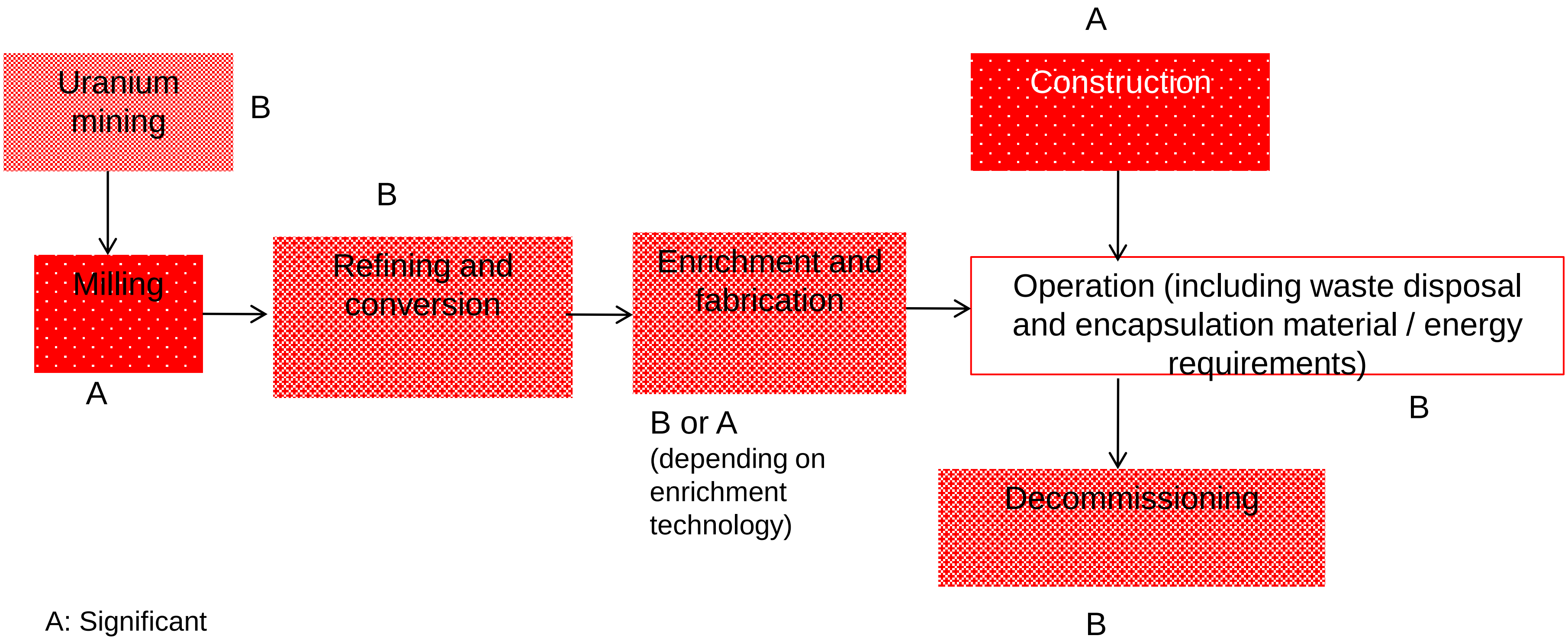
Based upon the review of the literature, the key hotspots in the nuclear life cycle i.e. the most important sources of LCEs, can be identified. These are shown below. For UK power plants, the key life cycle stages are the construction of the power plant (where large amounts of concrete and reinforcing steel are required) and the milling stage where energy is required in the process. Uranium mining, refining and conversion and enrichment and fabrication are typically less energy intensive. The operational phase also includes material (steel) and energy requirements for storing the radioactive waste. Emissions from decommissioning are expected to be less significant



A: Significant
B: Less significant
C: Negligible

Geographical factors - Nuclear

- The construction of the power plant will require large amounts of steel and concrete, and smaller amounts of other material. Construction materials can be either sourced in the UK or internationally. For steel and aluminium it is assumed (based on current trends) that, respectively, 45% and 27% are sourced in the UK. Concrete is assumed to be sourced entirely from within the UK.

- Life cycle emissions from the construction phase are significant in comparison to other LCEs and so the source of raw materials will contribute significantly to overall LCEs.

- Milling is one of the key stages influencing LCEs and is associated with high energy requirements. The concentration of the natural uranium will influence these requirements. As milling is undertaken at the location where uranium is sourced, the source of uranium plays a key role in estimating LCEs.

- The carbon intensity for steel, concrete and other materials in the UK and the grid intensity (assuming grid electricity will be used rather than onsite generation) at the mining / milling location and in the UK will play a key role in estimating the UK share of overall LCEs currently and in the future.

Base case scenario assumptions

RICARDO-AEA

The assumptions for our base case are shown in the table to the right.

The base case assumes that the carbon intensity of materials will develop in accordance with the IEA ETP Base scenario and that all uranium is sourced from Australia.

Construction and fuel cycle data were based on Kunakemakorn (2012) based on UK EPR. This study was used due to its transparency and availability of data.

Power plant parameters

Parameter	
Technology	PWR
Capacity (MW)	3300 MWe
Efficiency	35%
Load factor (%)	85%
Burn-up rate, GWd/t U	70
Lifetime (years)	60

Burn rate is a measure of how much energy is extracted from the nuclear fuel

Parameter	Base scenario assumption
Power plant parameters	As listed in the table below.
Source of raw material for construction	Steel: 45% UK, Aluminium: 27% UK, Other 20% UK, cement and concrete: all from UK
Source of Uranium (i.e. mining / milling location)	All from Australia (OECD Other)
Other processes	Refinery, conversion, enrichment and fabrication: after milling, transported as yellow cake to UK where these process take place
Raw material carbon intensity	Base – based on the IEA 2 degrees scenario
Grid intensity (UK and other)	Base – based on the IEA 2 degrees scenario
Ore grade	0.1%
Mining	Underground
Type of enrichment	Centrifuge
Life cycle stages	Fuel transport was not included since emissions are insignificant. Decommissioning emissions were not included but waste disposal emissions were included as part of the operational phase

Comparison to previous studies

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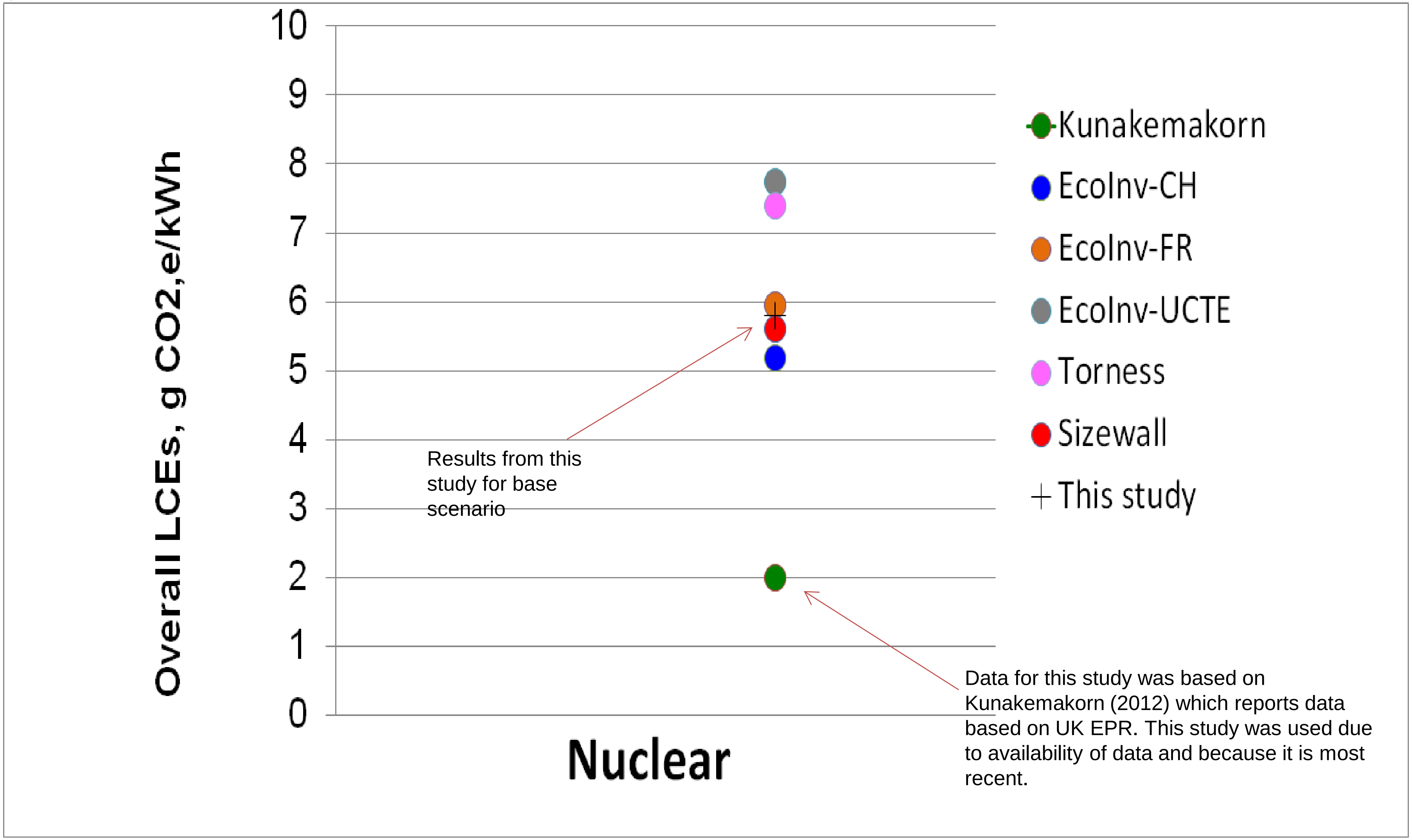
Based on the base scenario, LCEs from the nuclear life cycle in the UK are 5.8 g $CO_{2,e}$/kWh. This compares well with previous European studies as shown below.

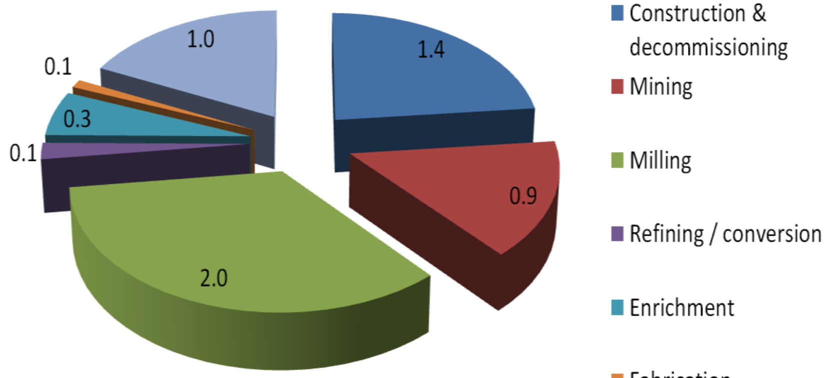


Base scenario: current and future LCEs

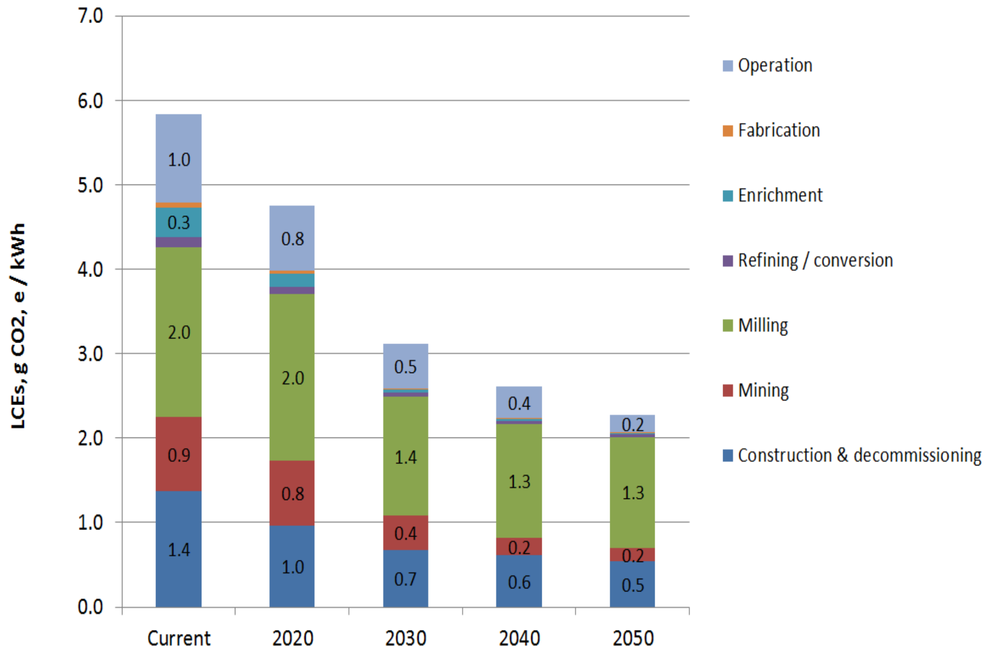
RICARDO-AEA

The results for the current LCEs for the base scenario for nuclear are shown below. Milling emissions make up about 34% of overall LCEs. Construction and decommissioning is the next major contributor making up about 24% of the life cycle emissions .

Operation emissions (as shown below) include emissions from the production of steel required for encapsulation, an ongoing requirement for waste disposal during the operation of the power plant through its lifetime.



Current LCEs – Base scenario

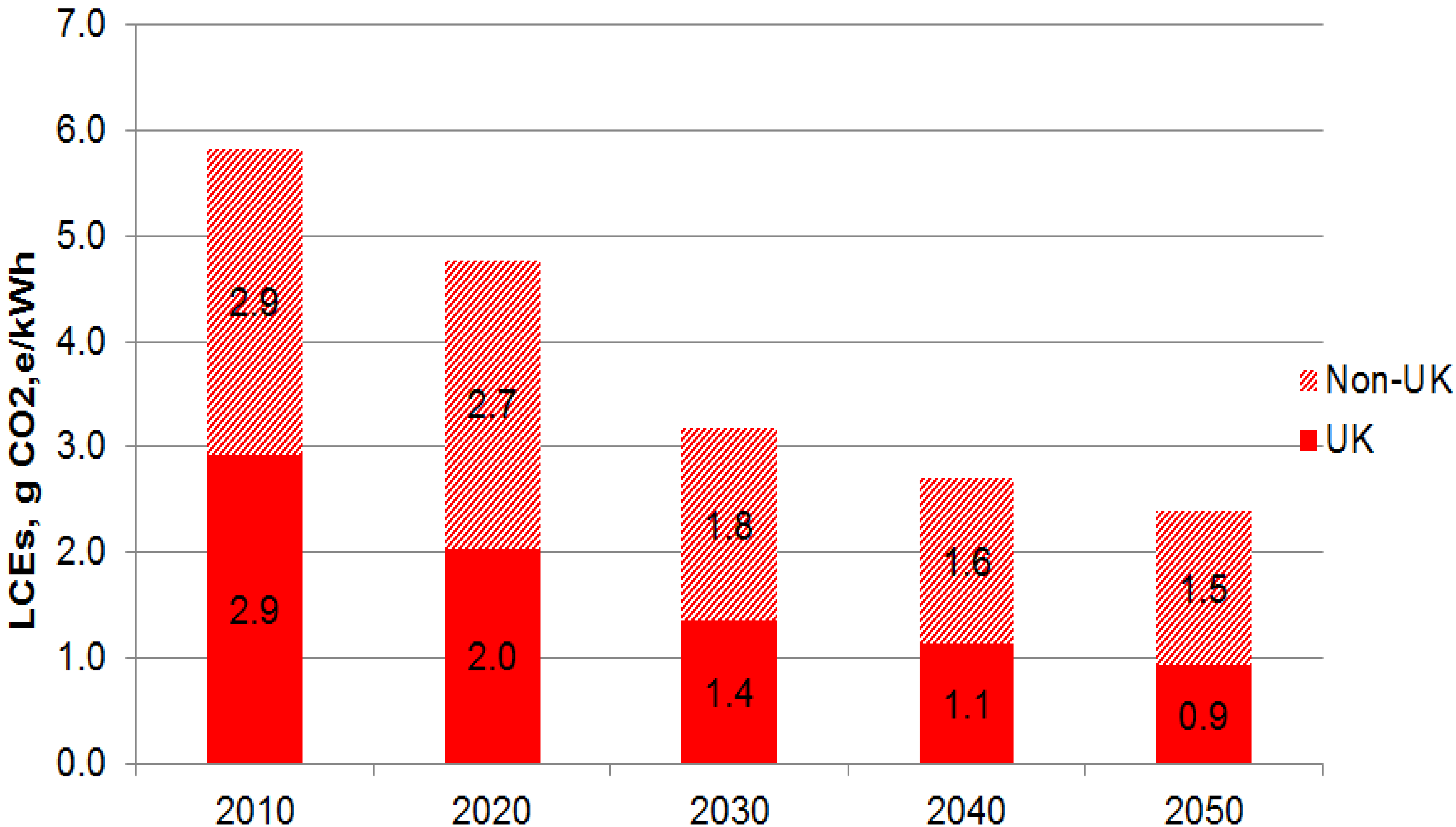


By 2050, overall LCEs reduce from 5.8 g $CO_{2,e}$/ kWh to 2.4 g $CO_{2,e}$/ kWh. This significant reduction (59%) is attributed to reductions in all activities as shown in figure above. The greatest proportional reductions are in enrichment, fabrication and mining due to reduction in grid intensity (the present study assumes electricity is supplied from the grid).

The operation phase emissions include those resulting from material (e.g. steel for storage vessels) and energy requirements for waste disposal

Location of emissions: base scenario

The share of UK emissions reduced from 50% currently to about 40% in 2050. While mining / milling emissions reduce overseas, construction emissions (which make a significant part of the overall LCEs) in the UK also decrease as a result of material and grid decarbonisation.



Sensitivity analysis: scenario definitions

RICARDO-AEA

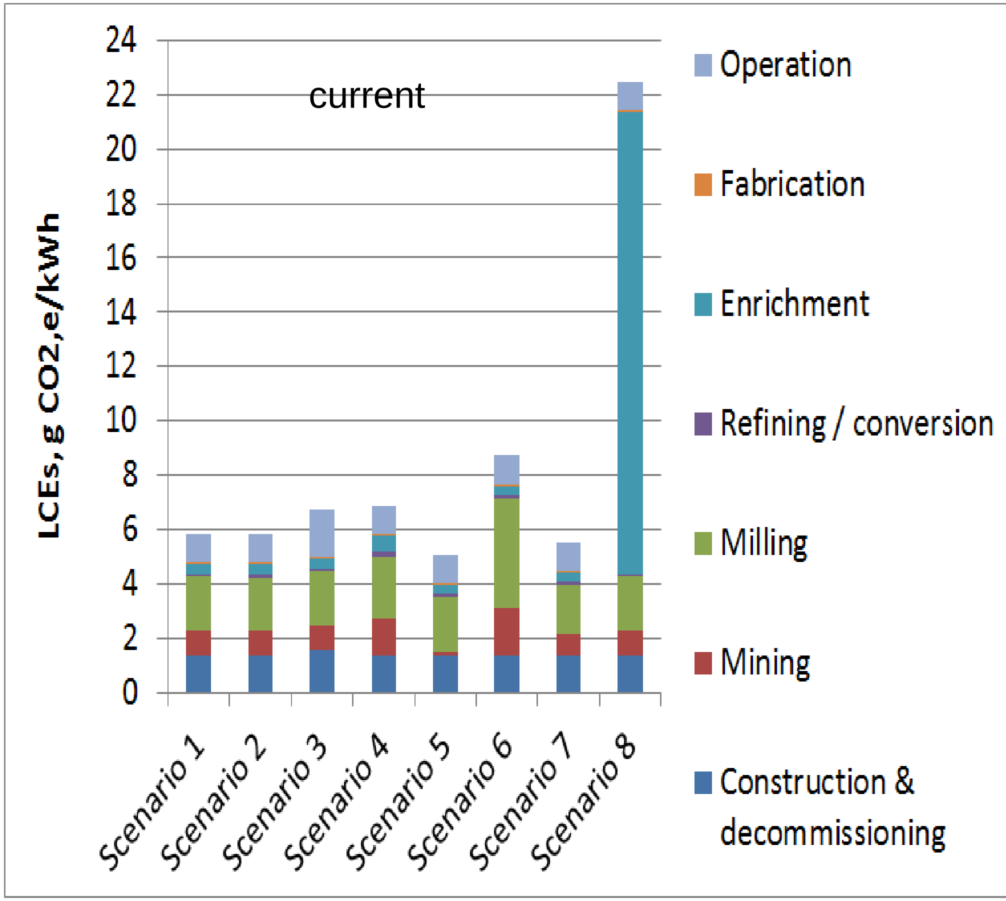
The spreadsheet LCE calculation tool was used to investigate the scenarios shown below.

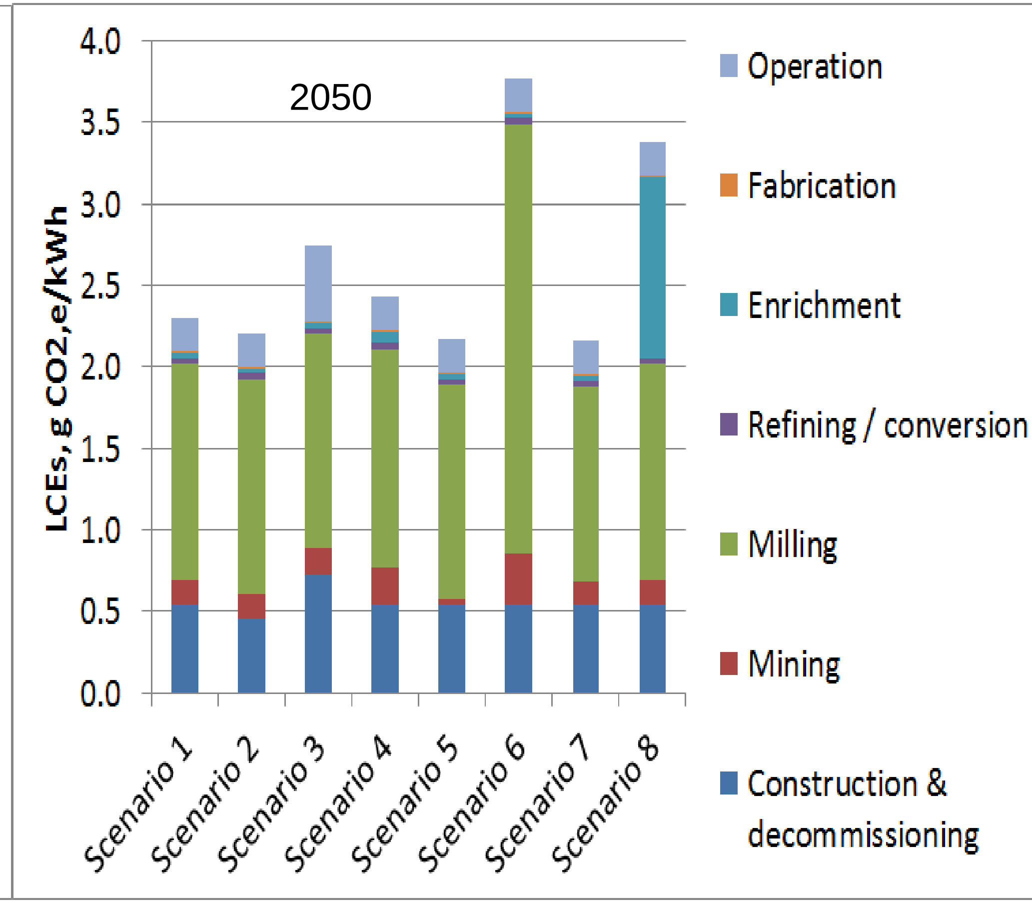
Scenario	Parameter tested	Comment
Scenario 1: Base	As described above	
Scenario 2	5% reduction in construction material requirement	There is a lot of variation in the literature in terms of materials (mainly steel and concrete) requirements. The reduction in material requirements for nuclear power plants, however, is not expected to be significant and so a figure of 5% is assumed.
Scenario 3	Source of raw material for power plant construction (steel and aluminium)	Assuming all construction material will be obtained from non-OECD countries
Scenario 4	Change of source of uranium	Mining and milling emissions are significant. If uranium were to be mined and milled in non-OECD countries, this will affect LCEs.
Scenario 5	Open cast mining instead of underground mining	These two mining methods have different energy requirements. Both types of uranium mines exist in Australia.
Scenario 6	Ore grade is 0.05% instead of 0.1%	Ore grade in the major Australian mines can vary from 0.05% to 0.2% depending on the location of the mine. The lower the uranium ore grade, the more material / energy requirement for extraction of the same amount of uranium.
Scenario 7	10% increase in burn-up rate	Burn-up rate is influenced by the type of reactor used. This is expected to lead to lower LCEs as more power will be produced for the same amount of uranium utilised.
Scenario 8	Enrichment method is gas diffusion instead of centrifuge	Gas diffusion has much higher energy requirements (by a factor of 50) than centrifuge.

Sensitivity analysis: results

RICARDO-AEA

Overall LCEs (current – 2050) for the different scenarios are shown below. The major factor influencing current LCEs is the type of enrichment (much higher electricity consumption for gas diffusion). In 2050, as the grid is decarbonised, the effect of the type of enrichment diminishes and the type of ore becomes a more important factor. The range of LCEs for all scenarios is 5.1 to 22.5 g CO_2/kWh and 2.2 to 3.8 g CO_2/kWh in 2050





Scenario as shown on slide 72

Conclusions - Nuclear

- For the base scenario, the total life cycle emissions could range from 5-22 g $CO_{2,e}$/kWh. This is in agreement with the range of figures reported by UK and European studies. Reduction in materials and grid emissions intensity to 2050 as projected by the IEA ETP 2DS reduces LCEs from nuclear power by around 60%.

- The main stages contributing to LCES are the milling, construction, operation (including encapsulation for waste disposal) and mining. Construction emissions make up about 25% of all LCEs currently and about 30 % in 2050. LCEs from the rest of the fuel cycle (e.g. fabrication, enrichment) are smaller making up less than 10% of overall LCEs.

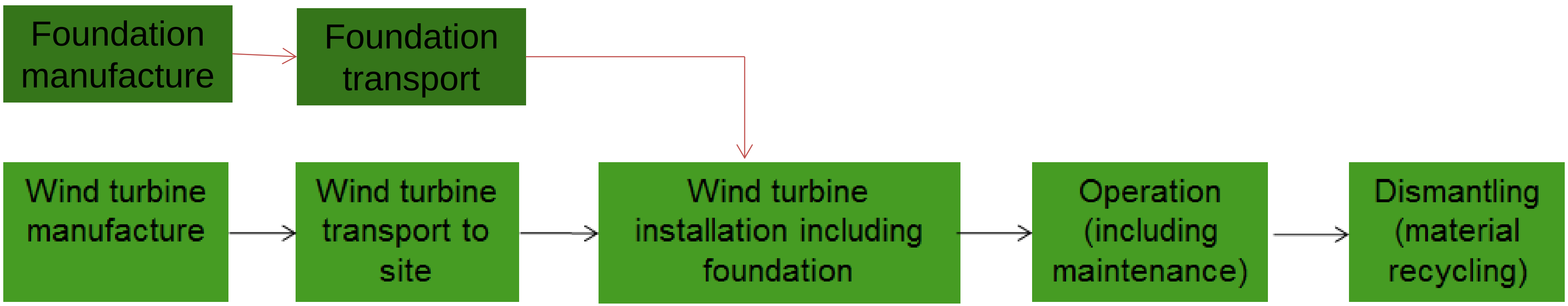
- The key factors which could influence LCEs are the type of enrichment, ore grade, type of mine and source of uranium as well as source of construction material and the grid intensity at the mining location (if no on-site generation). Currently, the method of enrichment (which is electricity-intensive) has a major effect but as the grid is decarbonised, this effect diminishes.

The wind power life cycle

The wind life cycle stage

Current and future LCEs were estimated for onshore and offshore wind. The wind life cycle consists of several stages as shown below. Manufacturing requires materials as well as energy. Emissions from raw material extraction (e.g. steel, aluminium and other metals) are included in this step.

The present analysis accounts for material and energy consumption for each of the processes above. In the literature, LCEs from the wind turbine cycle are usually broken down by turbine component rather than by life cycle stage (i.e. focussing on the manufacturing stage)



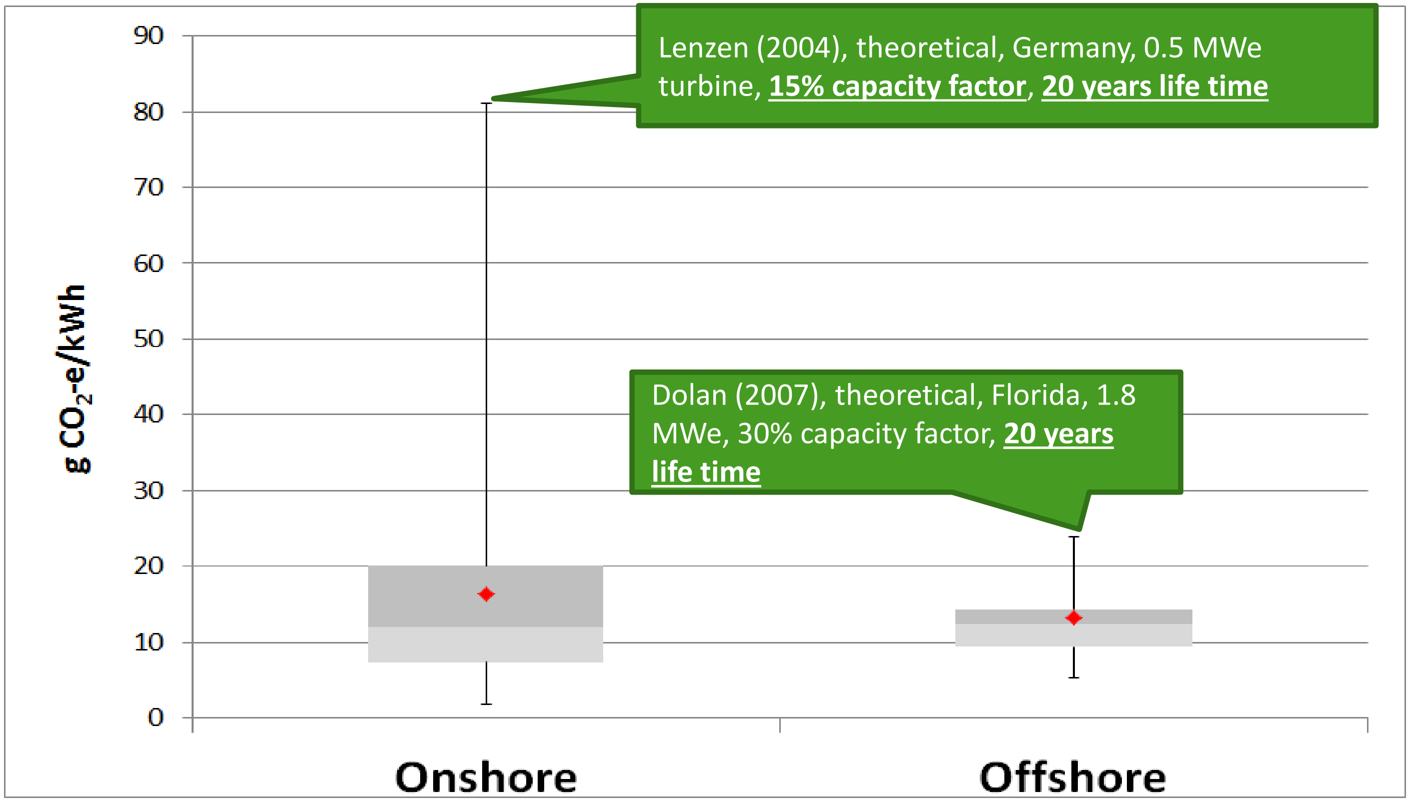
Overall LCEs: range in the literature

RICARDO-AEA

A review of LCEs from wind turbines is given in the Journal of Industrial Ecology (2012). Data points from the study are shown below. Most studies report LCEs below 20 g $CO_{2,e}$/ kWh for onshore wind and between 10 and 15 g $CO_{2,e}$/kWh for offshore wind. The lower LCEs for offshore wind are attributed to higher load factors for offshore wind turbines.

Lower end for onshore is based on a US study by Spitzley (2004), 0.5 MWe turbine, 30 years life time, 36% capacity factor

Lower end for offshore is based on a Vestas study (2006), 3 MWe turbine, 20 years life time, 54% capacity factor



Graph based on 107 data points for onshore and 16 data points for offshore (Journal of Industrial Ecology, 2012)

Range of assumptions in the literature

RICARDO-AEA

The range of assumptions in the literature is shown below. The variation in LCE reported by the literature is attributed to several key factors including (1) load factor, (2) lifetime (years), and (3) manufacturing location which affects grid intensity as well as carbon intensity of the raw material used.

Most of the early studies were on onshore wind turbines. Some of these studies assumed very high capacity factors and lifetimes and leading to low LCEs.

	Onshore wind	**Offshore wind**
Year of study	1995 - 2012	2000-2009
Location	UK, Italy, US, Brazil, Germany, Japan, Sweden, Denmark, Australia	North Sea, Baltic Sea
Capacity	150 kW – 6.6 MW	500 kW – 5 MW
Lifetime	10 – 100 years	20 years
Capacity factor	9% - 71%	29%, 30%, 46%, 54%

based on 107 data points for onshore and 16 data points for offshore (Journal of Industrial Ecology, 2012)

Breakdown of LCEs

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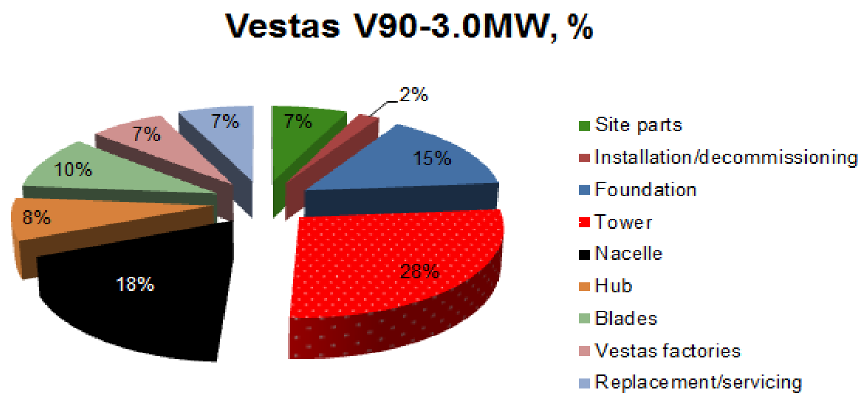
Typical breakdown of LCEs for the onshore wind life cycle is shown below. Most LCEs from the wind life cycle are associated with the manufacture of the wind turbine. Most LCEs are associated with the tower (mainly steel) followed by the nacelle and foundation. The key components for onshore foundations are steel and concrete while for offshore wind, foundations are mainly steel.

Aluminium is mainly required for the blades while copper is mainly used for cabling. Other materials used in wind turbines are plastics and glass.

Steel, iron and plastics make up more than 95% of the materials weight used in the manufacture of wind turbines (80-90% of total LCEs)



Current emission hotspots

Based upon the review of the literature, the key hotspots in the wind life cycle i.e. the most important sources of LCEs, can be identified. These are shown below. The wind turbine manufacture (for onshore wind) and foundation (for offshore wind) are the main contributors to LCEs.

A: Wind turbine manufacture → C: Wind turbine transport to site → A: Wind turbine installation including foundation → B: Operation (including maintenance) → C: Dismantling

A: Significant
B: Less significant
C: Negligible

Geographical factors - Wind

- LCEs from the manufacture of the wind turbine will be influenced by the carbon intensity of materials and transport as well as the grid intensity. The location where manufacturing takes place is thus of significance.

- Wind turbines installed in the UK are currently manufactured in Europe. This is expected to remain the case in the future.

- The location where the wind turbine is installed also affects LCEs. Locations with lower wind speeds result in lower load factor and higher LCEs. The water depth also affects LCEs from offshore wind as larger foundations will be required for deep water.

Base case scenario assumptions: Summary

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The scenario assumptions are given below.

Parameter	Base scenario assumption
Power plant parameters	As listed below
Manufacturing location	OECD Europe
Source of raw material for manufacturing	OECD Europe
Raw material carbon intensity	Low – based on the IEA 2 degrees scenario
Grid intensity	Low – based on the IEA 2 degrees scenario

Power plant parameters

Parameter		
Technology	Onshore	Offshore
Capacity (MW)	3	5
Load factor	27%	41%
Lifetime, years	20	20

The present analysis estimates LCEs based on UK conditions and investigate the effect of the parameters listed above. In addition, the geographical factors (e.g. turbine manufacturing location) are also investigated. Future LCEs are estimated based on future materials and grid emissions intensity scenarios. Emissions (now and in the future) are separated into UK and non-UK emissions

Overall LCEs: range in the literature

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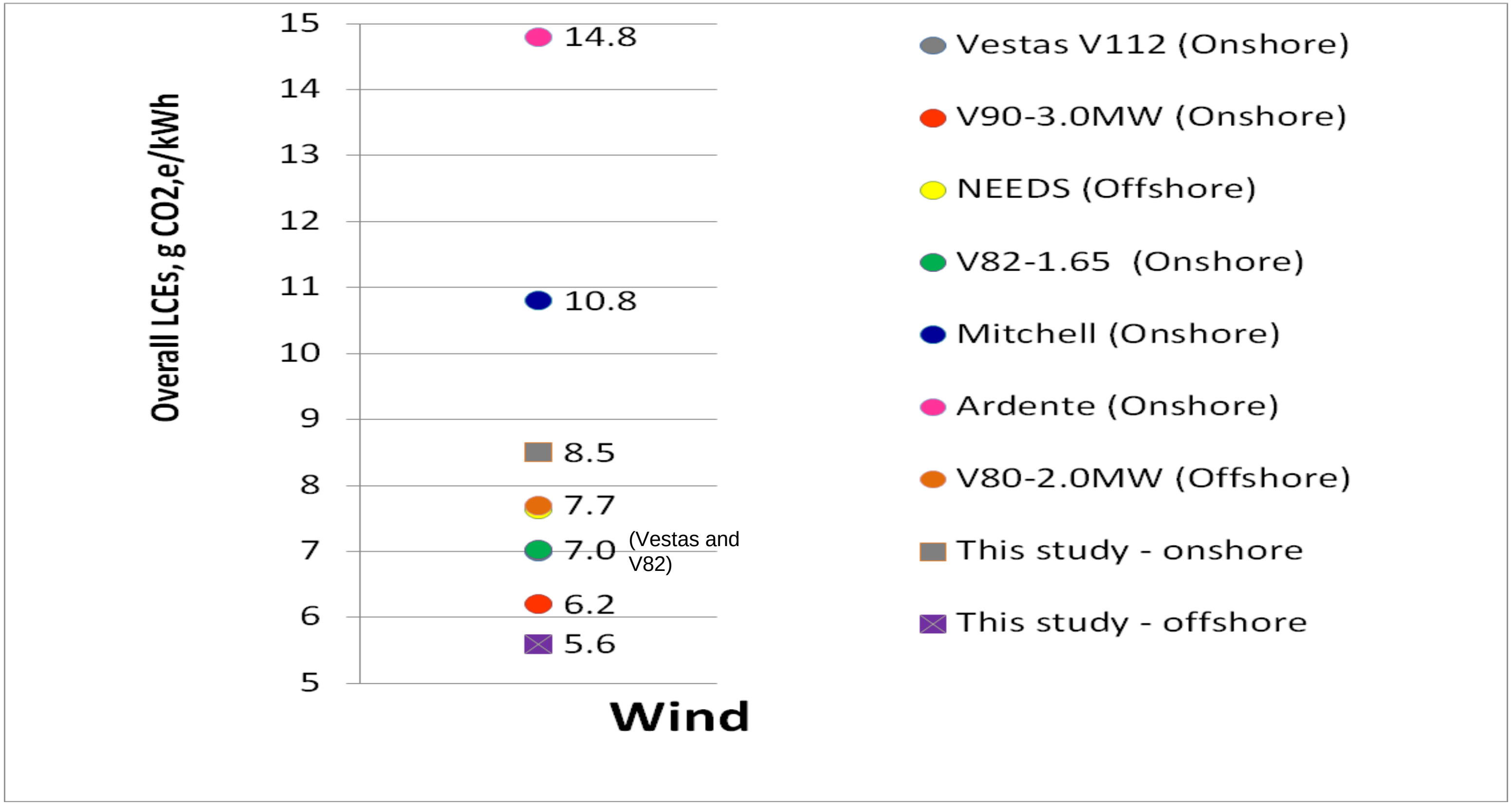
Total LCEs estimated from this study are compared with data available from the literature in the figure below. Our estimates are in agreement with the literature. Differences are due to different assumptions for the capacity factor and other technology parameters.

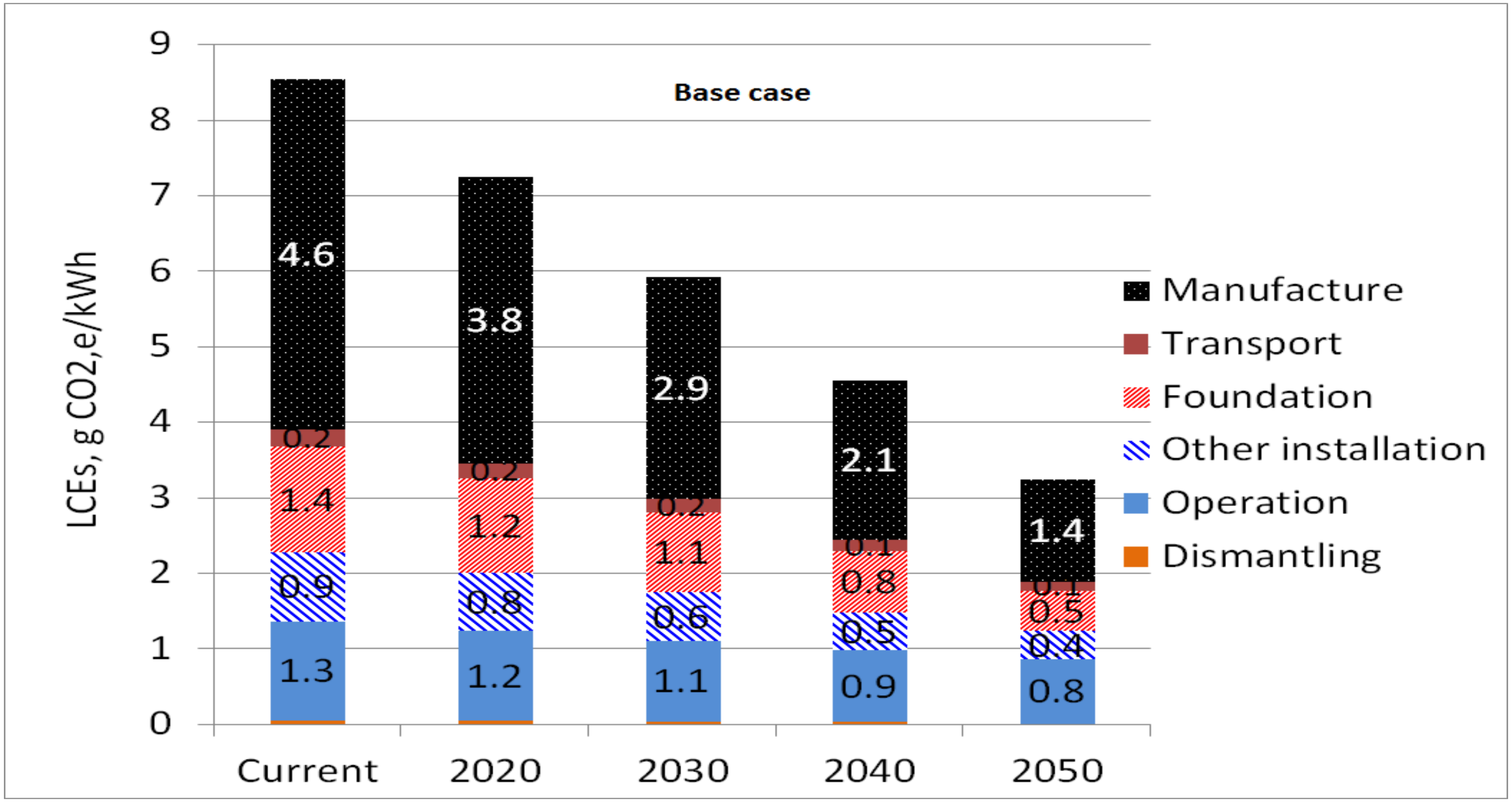


Offshore LCEs estimated for this study are for a 5 MW turbine. Material requirements have been scaled based on data for a different size turbine. Overall, a larger sized turbine is expect to be associated with lower LCEs, than a small turbine. This is because the LCEs from the material input don't scale on a linear basis. Running the spreadsheet calculation tool for a 2 MW turbine size gives LCEs of 11 g $CO_{2,e}$/kWh.

Base case scenario: onshore

RICARDO-AEA

Most LCEs from the wind cycle arise from the manufacture stage. Emissions from foundations are associated with the embedded emissions in materials (steel, plastics, copper, concrete). ‘Other installation’ emissions are associated with materials required for transformers and other equipment (steel, aluminium, copper, glass, lubricants) in addition to diesel required for installation.

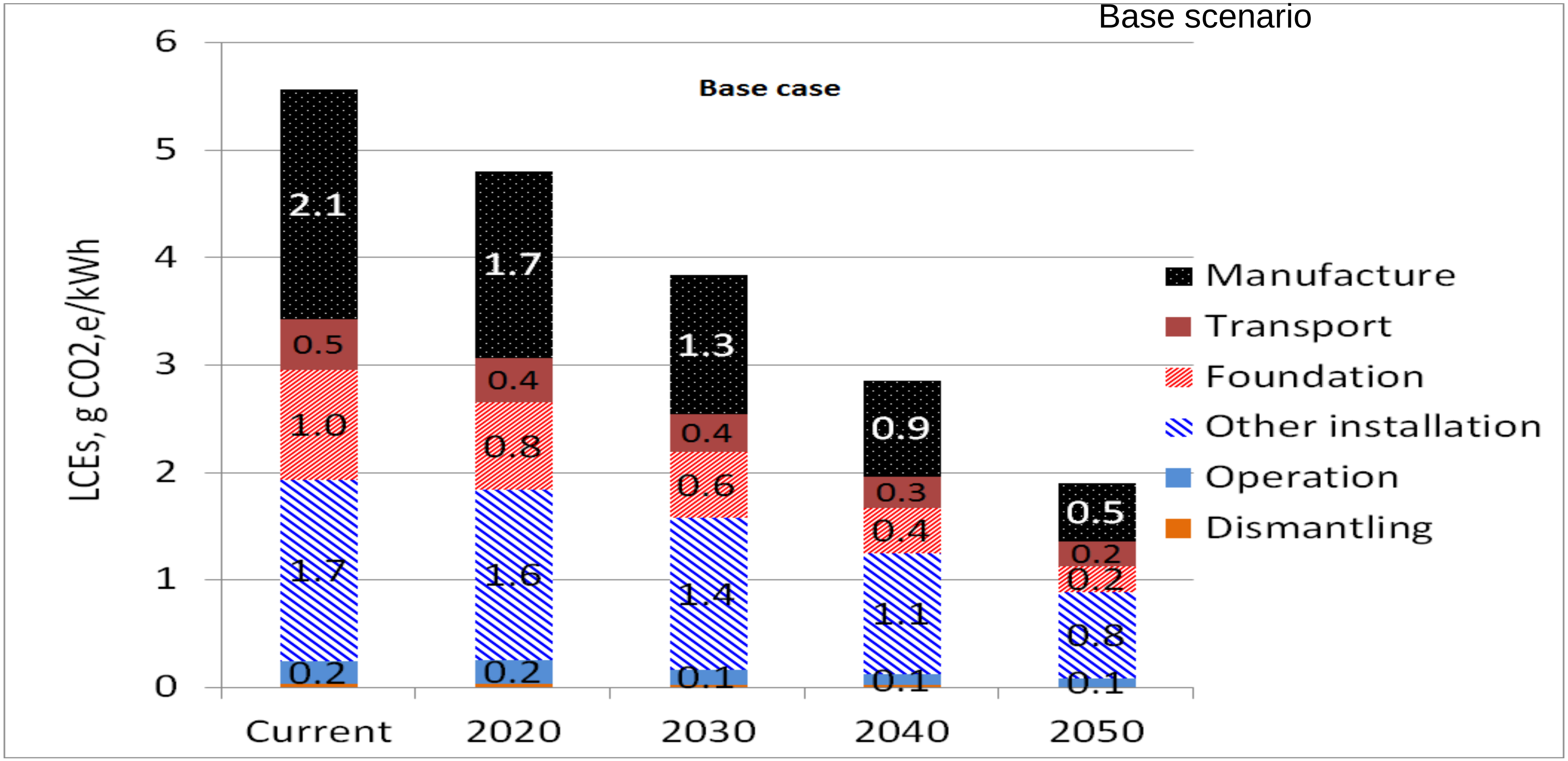


By 2050, overall LCEs reduce from 8.5 g $CO_{2,e}$/ kWh to 3.2 g $CO_{2,e}$/ kWh (60% reduction), as a result of reduction in manufacturing (both turbine and foundation) LCEs (due to lower material and grid intensity) . The key life cycle stages contributing to LCEs in 2050 are the wind turbine manufacture (56%) and installation (27%).

Base case scenario: offshore

RICARDO-AEA

The results for the current LCEs for the base scenario for off-shore wind are shown below. Current LCEs are estimated to be 5.6 g $CO_{2,e}$/kWh. Manufacturing LCEs per kWh are lower due to the larger size of turbine (5 MW compared to 3 MW for onshore): the greater materials requirement (and associated emissions) for a larger turbine is more than offset by the increased power output. For a 3 MW offshore turbine with 27% capacity factor (as assumed for onshore), total LCEs are 12 g $CO_{2,e}$ / kWh, mainly due to the foundation and other installations (57%). The LCEs associated with the foundation for the 5 MW turbine (base case) are 2.7 g $CO_{2,e}$/kWh (current) and 1 g $CO_{2,e}$/kWh (in 2050).

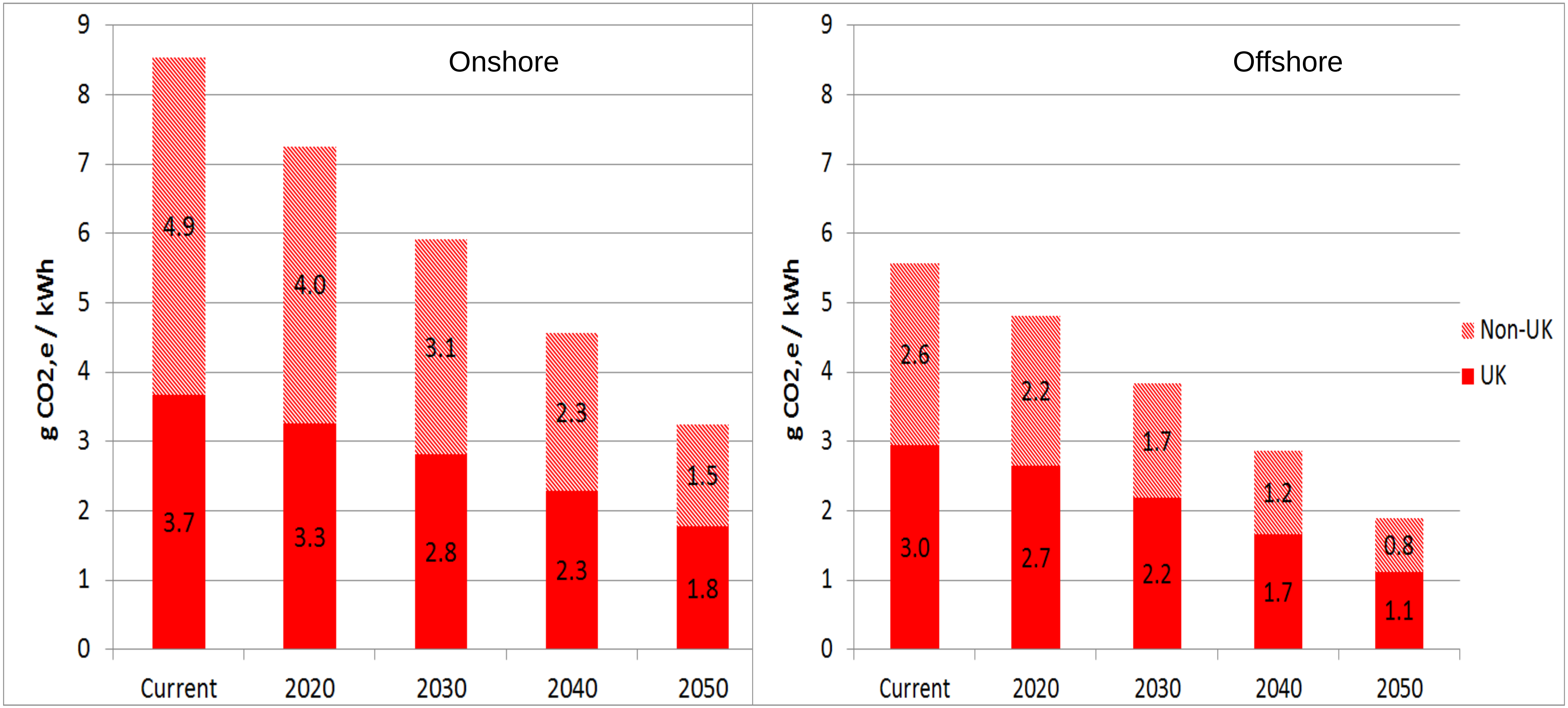


For offshore wind, LCEs drop by about 65% reaching 1.9 g $CO_{2,e}$/kWh in 2050. The key life cycle stages contributing to LCEs in 2050 are manufacture (25%) and installation including foundation and cabling (53%).

Location of LCEs: base scenario

RICARDO-AEA

UK vs non-UK emissions are shown below for onshore and offshore wind. Currently, most emissions for onshore wind are non-UK based. In 2050, most emissions for both onshore and offshore wind will be based in the UK.



Sensitivity analysis: scenario definitions

RICARDO-AEA

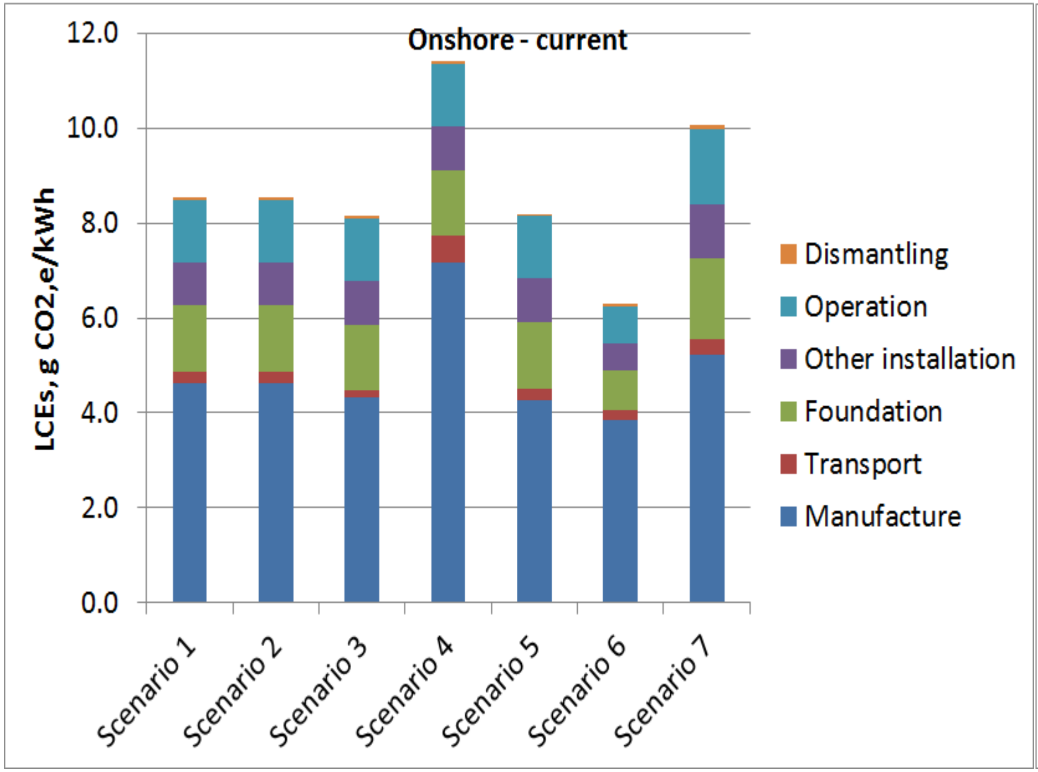
The LCEs calculation spreadsheet was used to test the sensitivities listed in the table below.

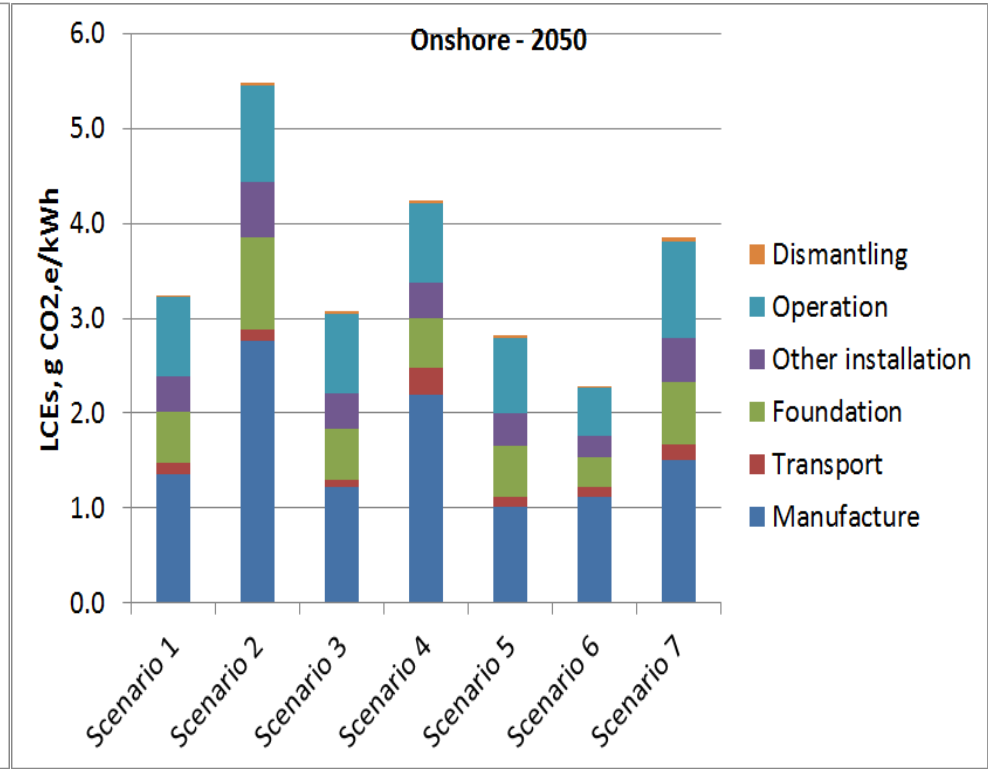
Scenario	Parameter tested	
Scenario 1: Base	As described above	
Scenario 2	Alternate material carbon intensity and grid intensity scenario (based on IEA's 4 degrees scenario)	This includes manufacturing (wind turbine) material intensity as well as material used in the foundations, cables, transformers, etc. It also includes increase in grid intensity at the manufacturing site.
Scenario 3	Manufacturing in the UK	This also means that raw material required for the wind turbine is sourced in the UK
Scenario 4	Manufacture in non-OECD country	Raw material sourced locally too
Scenario 5	Reduction in material requirements for the wind turbine by 5% / 10 years	It is possible that future wind turbines and foundations will use less material.
Scenario 6	A larger size turbine (5 MWe for onshore and 8 MWe for offshore)	The scale up for material (e.g. steel) requirements was based on data from Vestas turbine sizes. An exponential term was developed based on data available and used to scale up material requirements.
Scenario 7	Lower load factors, reducing to 22% for onshore and 36% for offshore	There is disagreement in the literature on load factors for onshore and offshore wind turbines.

Sensitivity analysis: results (overall LCEs)

RICARDO-AEA

Results for on-shore wind are shown in below. Considering current LCEs, the key factors which could influence LCEs are the manufacturing location (non-OECD vs OECD) and the load factor. A larger turbine size leads to a reduction in LCEs. Increasing the wind turbine capacity from 3 MW to 5 MW reduces LCEs by 25-30%.





Scenario description as shown on slide 86

Our analysis shows that the material and grid intensity alternate scenario (IEA's 4DS scenario) does not influence current LCEs but increases 2050 LCEs by 70%.

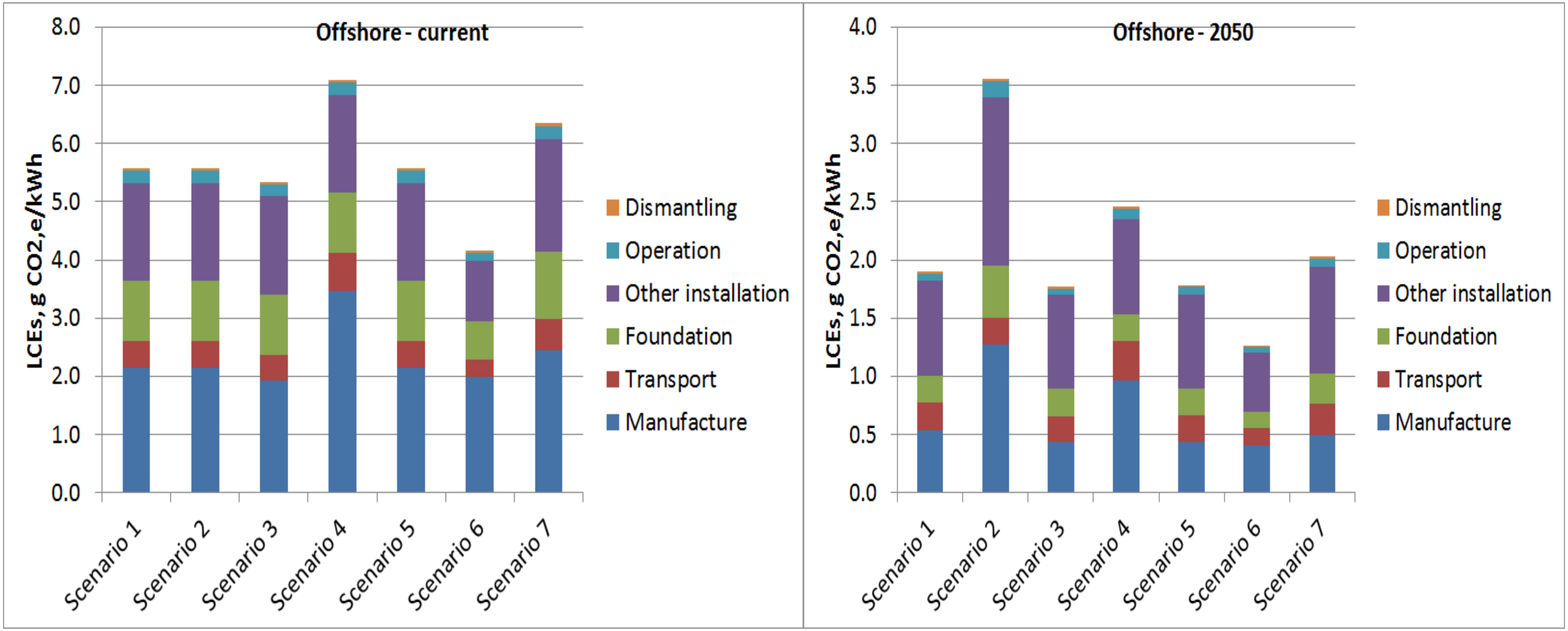
The analysis also shows that UK manufacturing (Scenario 3) reduces LCEs by 5% while non-OECD manufacturing (Scenario 4) increases LCEs by about 35%.

Reducing the load factor (scenario 7) increases LCE by about 20%.

Sensitivity analysis: results (overall LCEs)

RICARDO-AEA

Results for off-shore wind are shown in below. Similar to onshore wind, the factors which could influence current LCEs are the manufacturing location (non-OECD vs OECD) and the load factor. A larger turbine size leads to a reduction in LCEs. Increasing the wind turbine capacity from 5 MW (as in the base case scenario) to 8 MW reduces current LCEs by 25% and future LCEs by about 30%.



Scenario description as shown on slide 86

Alternate scenarios for material carbon intensity and grid intensity (based on IEA's 4DS scenario) does not influence current LCEs but increases 2050 LCEs by 90%.
The analysis shows that UK manufacturing (Scenario 3) does not influence LCEs significantly. Non-OECD manufacturing (Scenario 4), on the other hand, increases LCEs by 25-30%.
Reducing the load factor (scenario 7) increases LCE by about 15%.

Conclusions - Wind

RICARDO-AEA

- For the base scenario, the total life cycle emissions are 8.5 g $CO_{2,e}$/kWh (reducing by 60% in 2050) for onshore wind and 5.6 g $CO_{2,e}$/kWh (reducing by 65% in 2050) for offshore wind. Estimates for current LCEs are in agreement with the range of figures reported in the literature and for previous UK studies. The estimated overall LCEs for the base scenario for offshore wind are, however, on the low side. This is attributed to the high load factor and large turbine size assumed for this study.

- The main factors affecting LCEs currently and in the future are:

  - the manufacturing location: UK manufacturing reduces LCEs slightly while manufacturing in non-OECD countries increases current and future LCEs by 25-35%.

  - the load factor: reducing the load factor for onshore wind from 27% to 22% increases LCEs by 20%. For offshore wind, reducing the load factor from 41% to 36% increase LCEs by 15%.

  - the carbon intensity of raw materials used in manufacturing the wind turbine: switching from the IEA 2DS to the 4DS scenario increases LCEs by 40% in 2040 and 90% by 2050.

- In comparison to the base scenario, manufacturing in the UK (vs mainland Europe) does not lead to significant changes in LCEs.

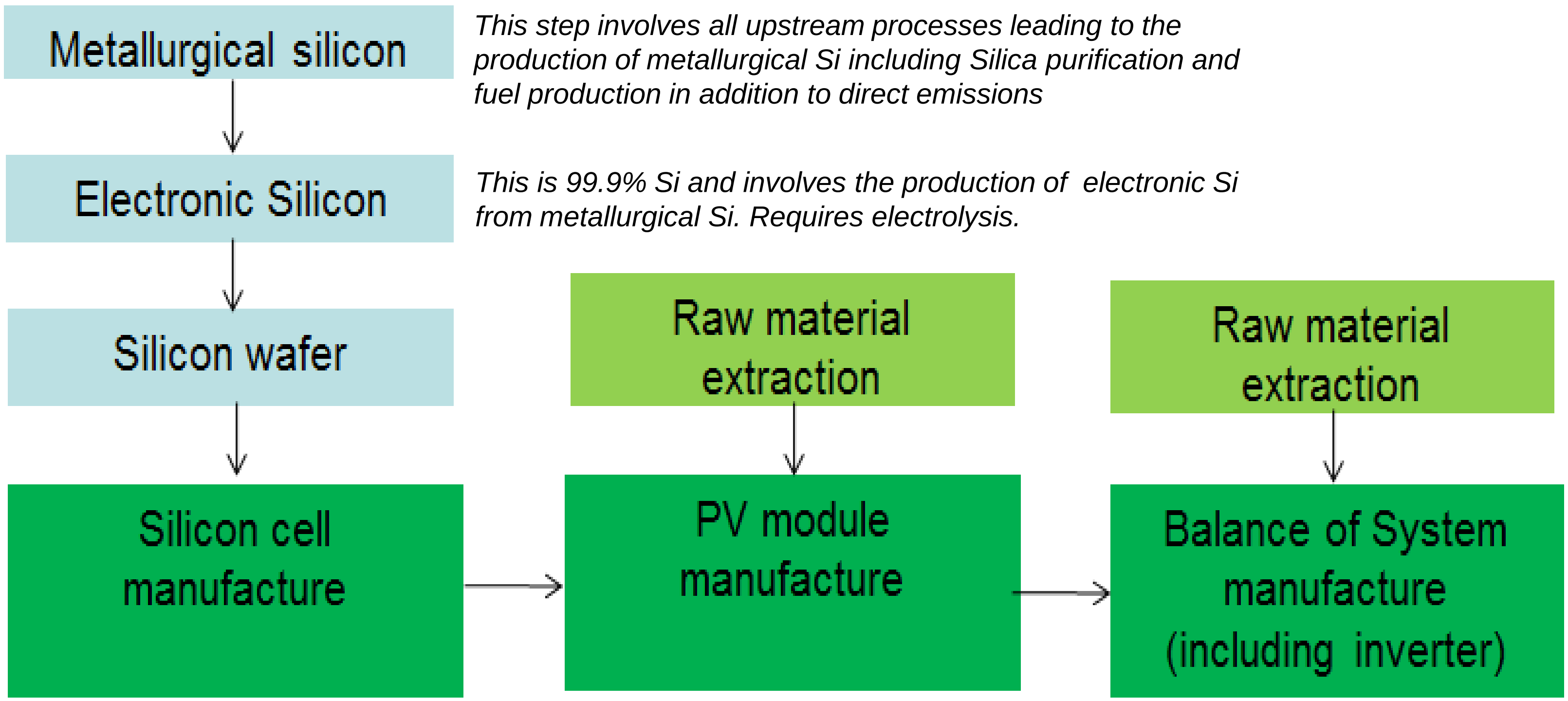
- Increasing the size of wind turbines by 60-70% reduces LCEs by 25-30%.

The solar PV life cycle

Solar PV life cycle

RICARDO-AEA

Current and future LCEs were estimated for mono-crystalline silicon PV modules, poly-crystalline silicon PV modules and Cadmium Telluride (CdTe) PV modules based on UK conditions. The key stages in the Si-based solar PV life cycle are shown below.

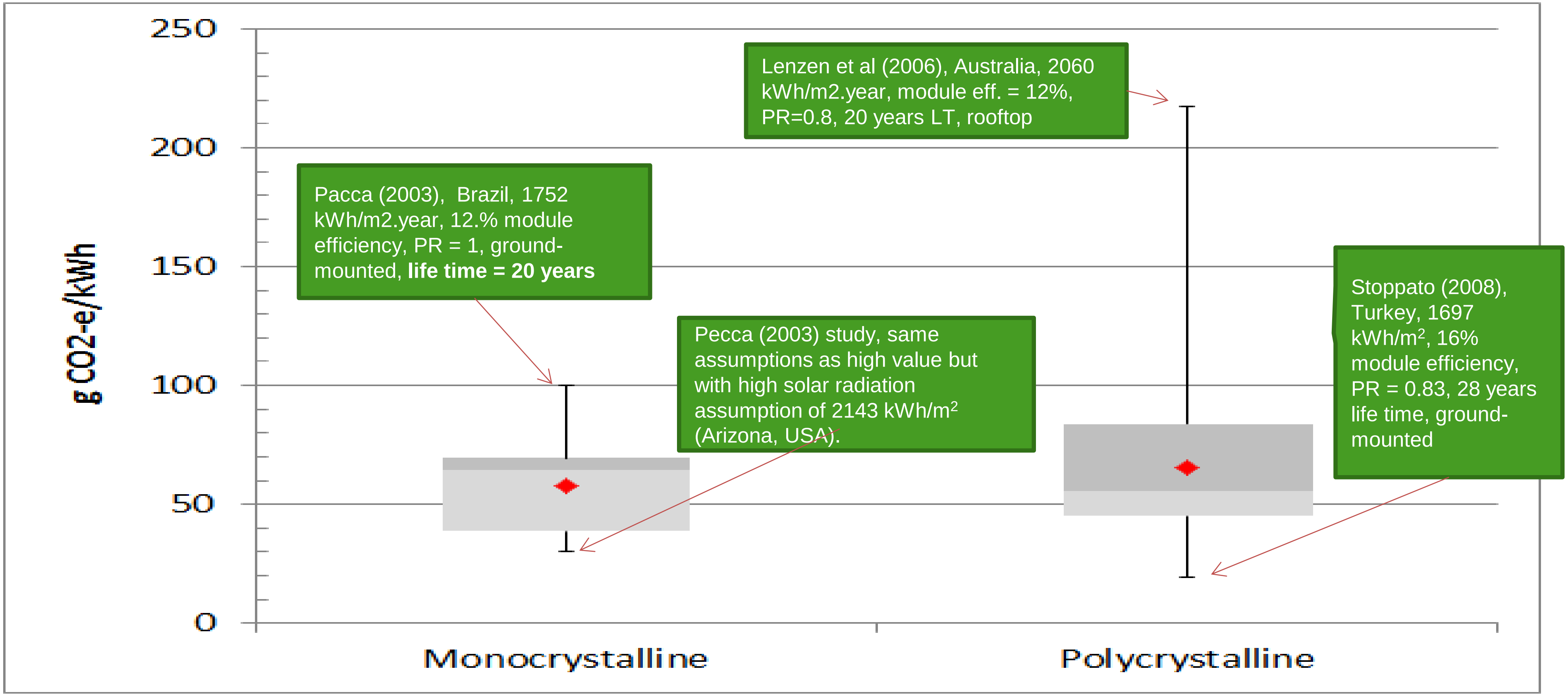


- The silicon-based PV solar life cycle consists of several stages as shown above. The silicon cell manufacture is an energy intensive process.
- Raw material extraction for PV module and Balance of system (BoS) manufacture includes the production of steel, aluminium and other metals.
- The present analysis accounts for material and energy consumption for each of the processes described above.

Range of total LCEs

RICARDO-AEA

A detailed analysis of recent studies on LCA of solar PV has been provided in the Journal of Industrial Ecology, 2012. The graph below shows the range of LCEs for the studies reviewed. The graph is based on 13 data points (9 rooftop, 4 ground-mounted) for mono-crystalline and 28 for poly-crystalline (21 rooftop, 7 ground-mounted).
The average is 58 g $CO_{2,e}$/ kWh for Monocrystalline Si PV and 65 g $CO_{2,e}$ for polycrystalline Si.



Limited studies are available on LCEs of CdTe and other thin-film technologies. Most studies on CdTe PV systems report a range of 20-30 g CO2,e/kWh.

Range of assumptions in the literature for Si-based PV module studies

The ranges of assumptions for the studies presented in the graph on the previous slide are shown in the table below. The variation in LCE reported by the literature is attributed to several key factors including

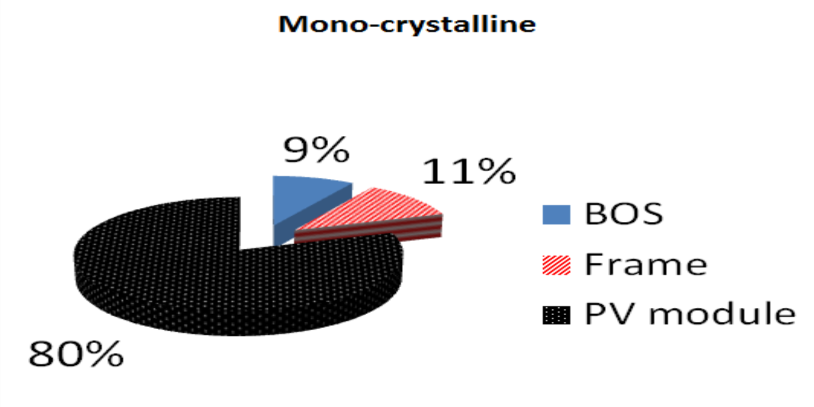
(1) solar radiation (kWh/m^2): countries where solar radiation is higher will give lower LCEs,
(2) lifetime (years): most studies assume lifetime of 20 – 30 years. A higher lifetime will give lower LCEs.
(3) performance ratio (PR) defined as the proportion of solar radiation which is converted to electricity. A higher PR will give lower LCEs.
(4) whether the installation is rooftop-mounted (building integrated or standalone) or ground-mounted. The type of installation will affect insolation as well as material requirements for the balance of system (BOS)

Year of study	2000 – 2009
Location	Europe, US, Brazil, Switzerland, Greece, Japan, Turkey, Germany
Solar radiation, kWh/m^2	900-2143
Lifetime	20-30 years
Performance ratio	0.75-1
Module efficiency	12-17%
Mounting	Roof-top or ground

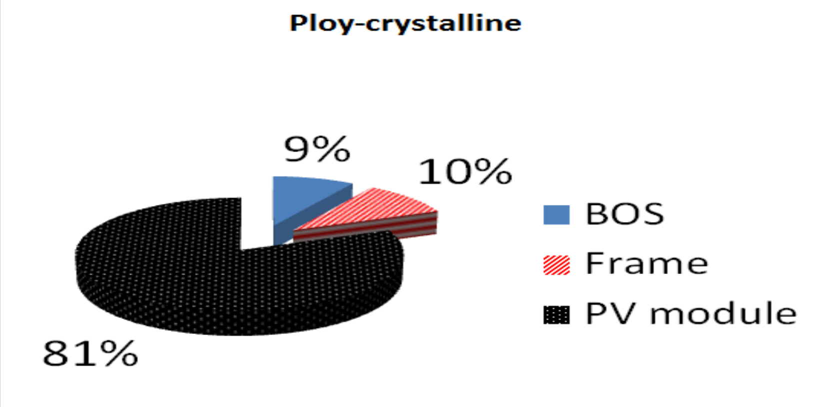
Assumptions for studies shown on previous slide

Typical breakdown of LCEs, Alsema, 2006

A frequently referenced study by Alsema (2006) compared LCEs for mono-crystalline Si, polycrystalline Si and CdTe. The breakdown of LCEs from this study and the assumptions are shown below.

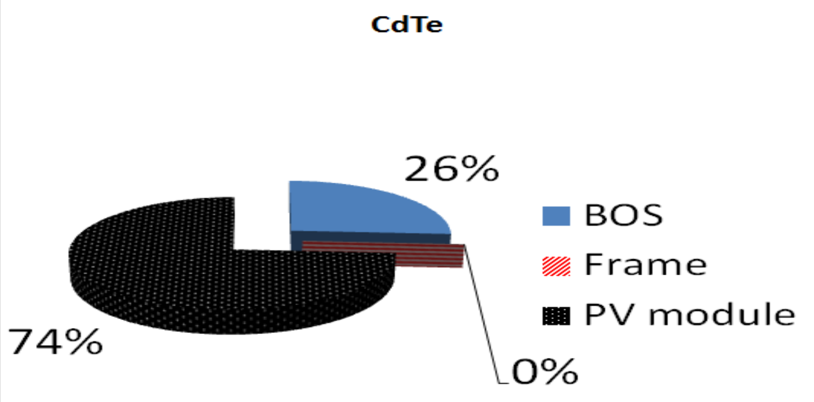


LCE = 35 g $CO_{2,e}$ / kWh



LCE = 32 g $CO_{2,e}$ / kWh

Assumptions
- Southern Europe
- Frameless module
- Ground-mounted
- 1700 kWh/m^2.year
- Efficiency: 9%, 13.2%, 14%
- PR = 0.75
- Lifetime: 30 years
- LCEs: 25, 32, 35 g/kWh



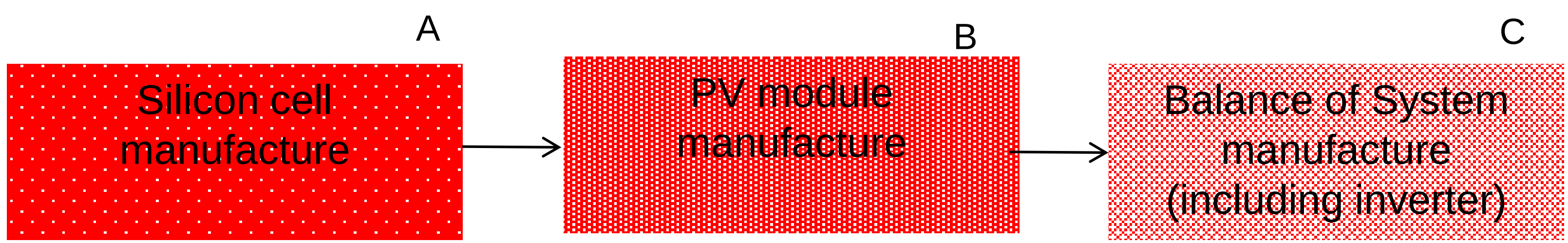
LCE = 25 g $CO_{2,e}$ / kWh

Geographical factors – Solar PV

- Solar radiation is the key parameter influencing LCEs from solar PV. The average solar radiation in the UK is around 1000 kWh/m^2
- Currently, the top Si-based PV manufacturers are based in China, Germany Japan and the US while the top CdTe module manufacturers are based in Germany and the US. Suppliers to the UK are mainly based in OECD countries. With the increasing installation of PV systems in the UK, plans are underway to start PV cell and module manufacturing operations in the UK. This will lead to additional UK-based emissions resulting from the manufacturing process.
- The decarbonisation of the grid worldwide will lead to lower emissions from the manufacturing of PV modules. As emissions associated with PV installations are lower than those from manufacturing, most LCEs will be based on countries where manufacturing occurs rather than where they will be installed.

Current emission hotspots

Based upon the review of the literature, the key hotspots in the solar PV life cycle i.e. the most important sources of LCEs, can be identified. These are shown below.. The PV cell manufacturing stage is most significant in terms of LCEs due to high energy consumption.



A: Significant
B: Less significant
C: Negligible

Base case scenario assumptions

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Assumptions for the base scenario are shown in the table below. The present analysis estimates LCEs based on UK conditions. The base scenario assumes that both PV cells and PV modules are manufactured in Europe. The manufacturing location, amongst other parameters is investigated as a sensitivity.

The present studies estimates LCEs for a 3 KWp PV systems. Other PV module parameters are listed in the table below.

Parameter	Base scenario assumption
PV module parameters and assumptions	As below
Grid intensity (UK and other)	Base – based on the IEA 2 degrees scenario
Carbon intensity of materials	Base – based on the IEA 2 degrees scenario
PV cell manufacturing location	OECD Europe
PV module manufacturing location	OECD Europe
Source of raw material for BOS	Steel: 45% UK, Aluminium: 27% UK, Other: 20% UK

PV module parameters

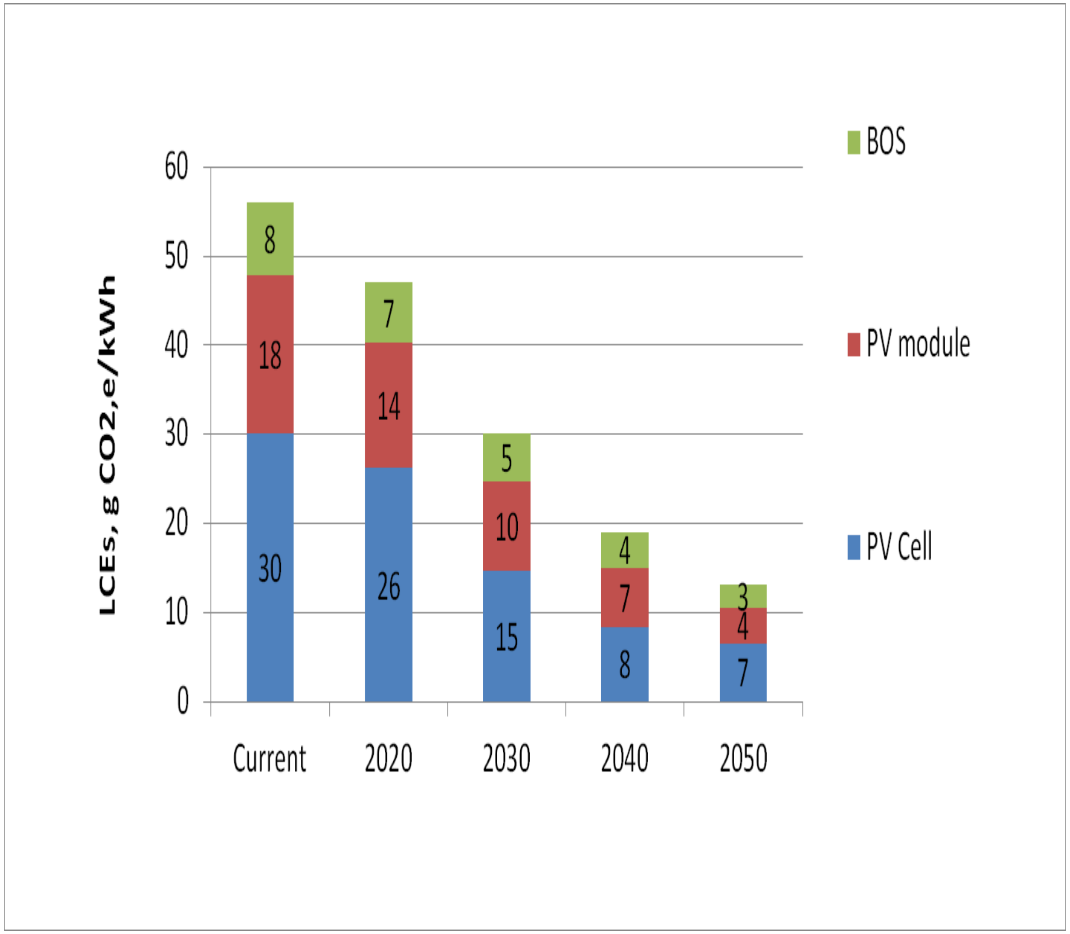
Parameter			
Technology	Mono-crystalline	Poly-crystalline	CdTe
Capacity (kW)	3	3	3
Module efficiency	14%	13%	9%
Performance ratio	0.75	0.75	0.75
Lifetime, years	30	30	30

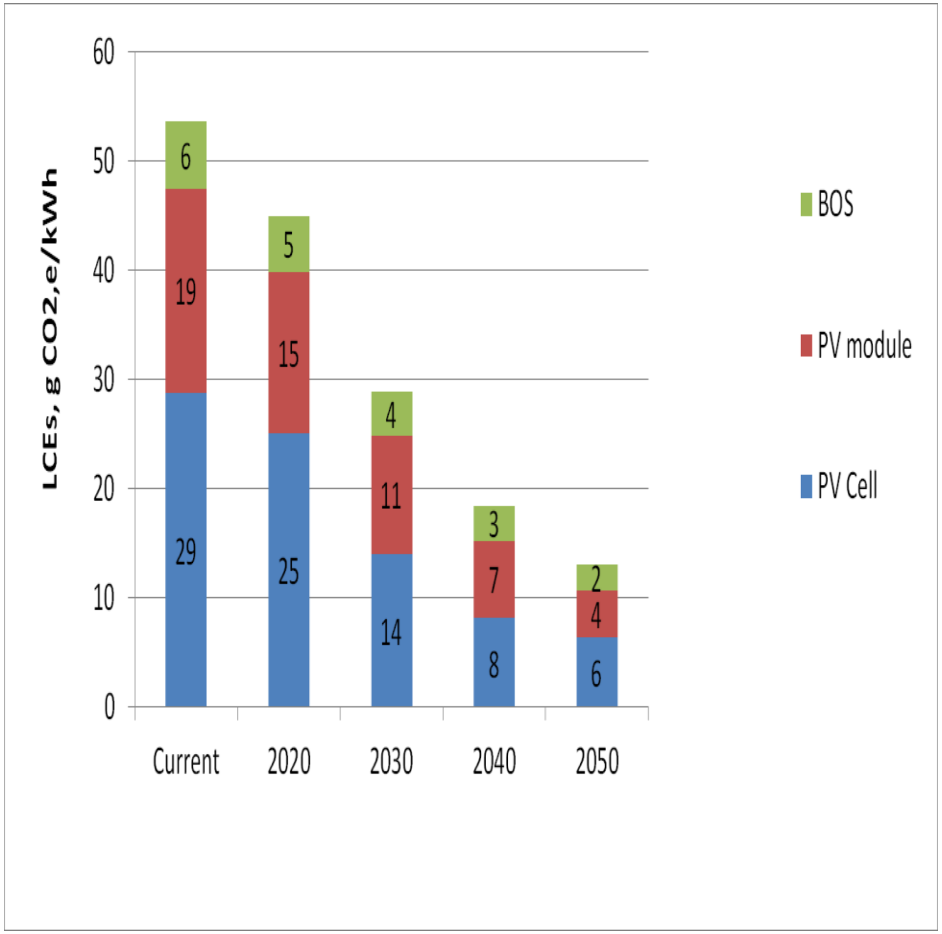
48 cells per module, 185 Wp module capacity, module area of 1.28 m^2.

Base scenario LCEs: Si-based modules

RICARDO-AEA

Results for the base scenario (current and 2050 LCEs) are shown below for both mono- and poly-crystalline Si.
The total current LCEs are 56 g $CO_{2,e}$ /kWh for mono-crystalline Si and 54 g $CO_{2,e}$ /kWh for poly-crystalline Si.
This is an agreement with results from the literature as shown in previous slides. Similar to the study by Alsema (2006), more than 80% of LCEs for both types of modules are attributed to the PV cell / PV module manufacturing phase.



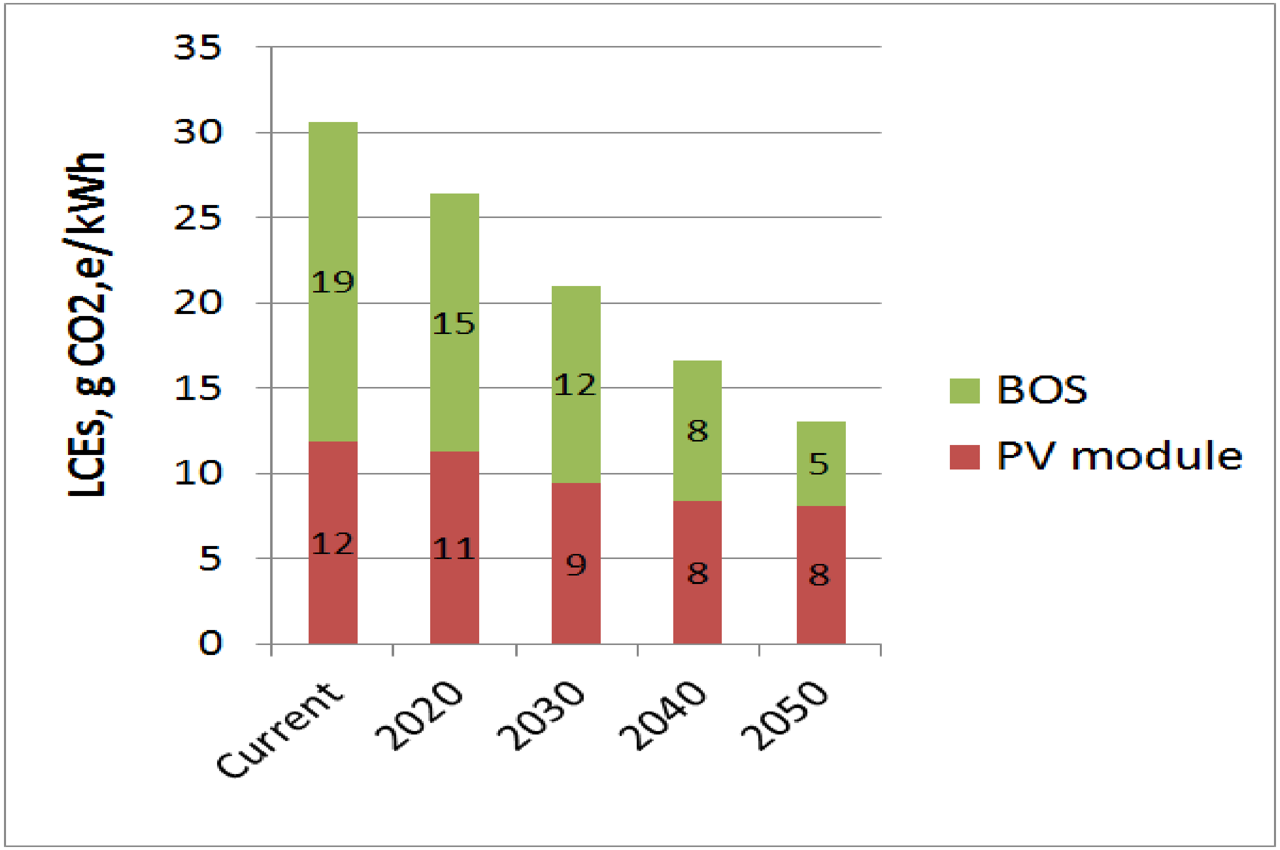


- ❑ The breakdown of LCEs is similar for both mono- and poly-crystalline Si.
- ❑ LCEs in 2050 reduce by 75% from current levels, for both technologies.
- ❑ The share of PV cell LCEs reduces in 2050 due to grid decarbonisation.

Base scenario LCEs: CdTe

RICARDO-AEA

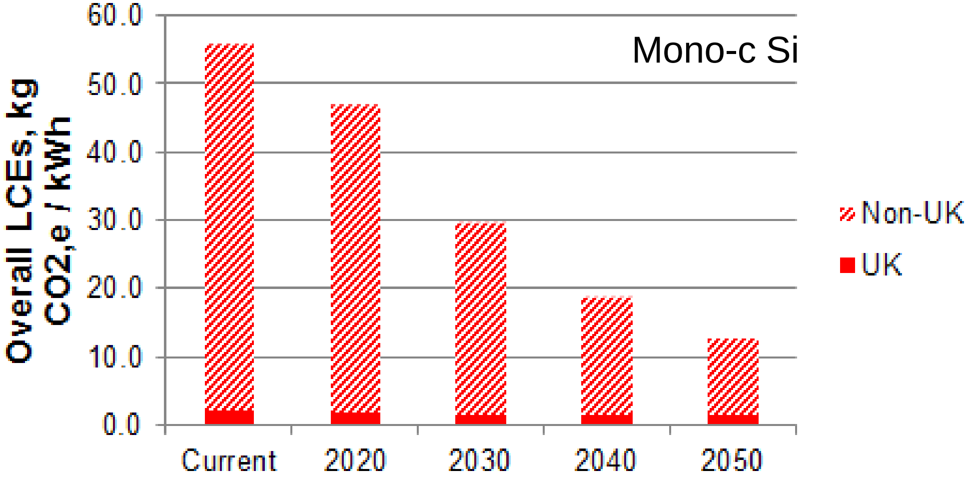
Results for the base scenario for CdTe are shown below. The total current LCEs are 31 g $CO_{2,e}$ /kWh. This is slightly higher than the results reported in the literature and can be explained by the lower efficiency assumed for this study (9%) and the lower solar radiation for the UK.

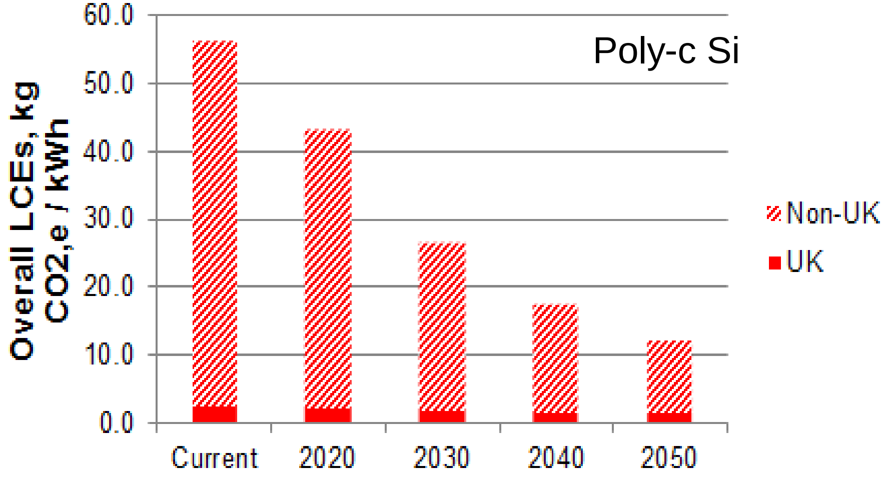


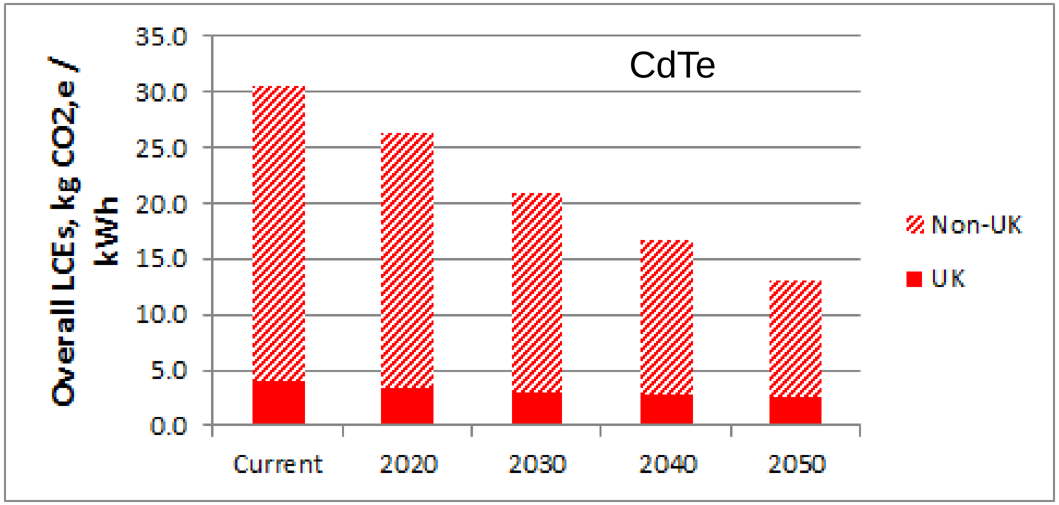
- By 2050, LCEs from CdTe reduces by about 60% in our base case.
- The reduction is lower for CdTe than for Si-based PV since the Si-based PV module manufacturing process is more intensive in terms of electricity consumption and so higher reductions are observed as a result of the expected decarbonisation of the grid.

UK vs non-UK emissions: Base scenario

RICARDO-AEA







- UK share of LCEs are higher for CdTe technology as here BOS LCEs emissions are slightly more significant than for Si-based PV modules.
- As discussed above, the base scenario assumes 45% of steel is sourced in the UK, 27% of aluminium is sourced in the UK and 20% of all other materials is sourced in the UK.
- The base scenario also assumes that PV cell and module manufacturing is in OECD countries.

Sensitivity analysis: scenario definitions

RICARDO-AEA

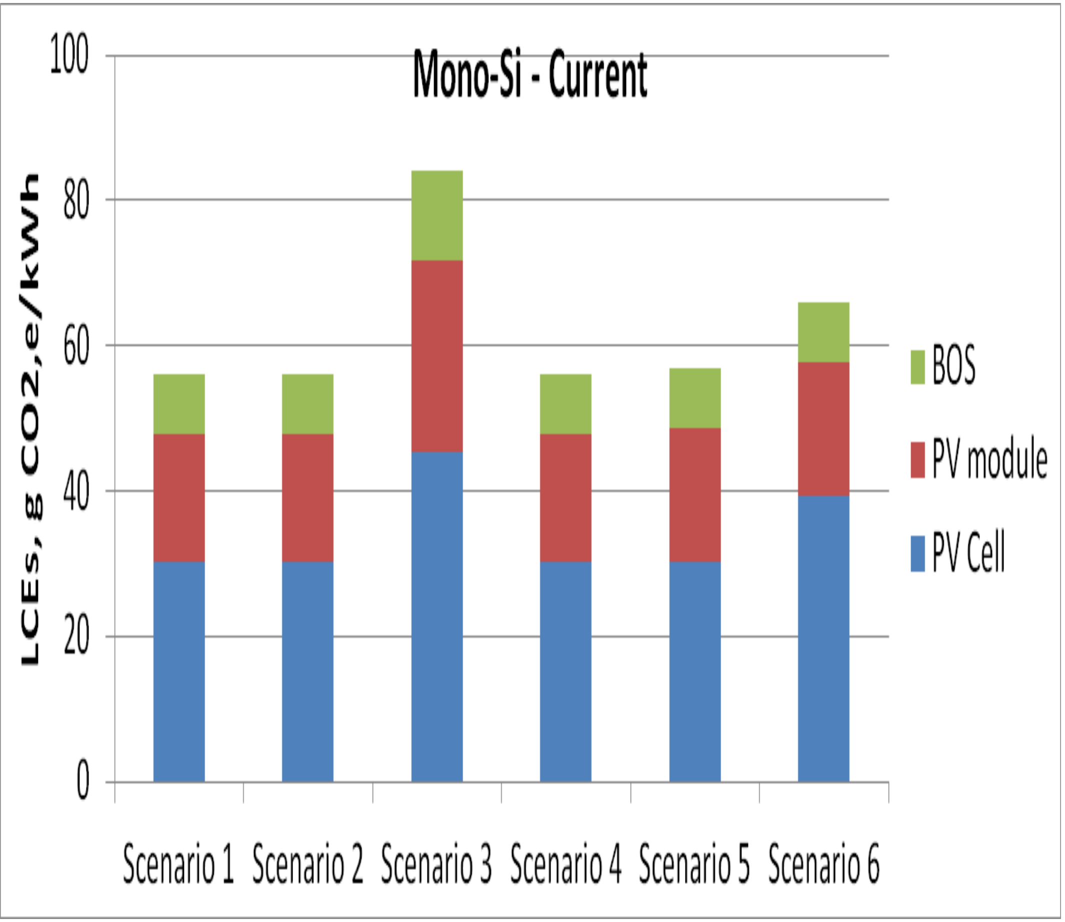
Several scenarios were tested as shown in the table below. These are compared to the base scenario in the following slides.

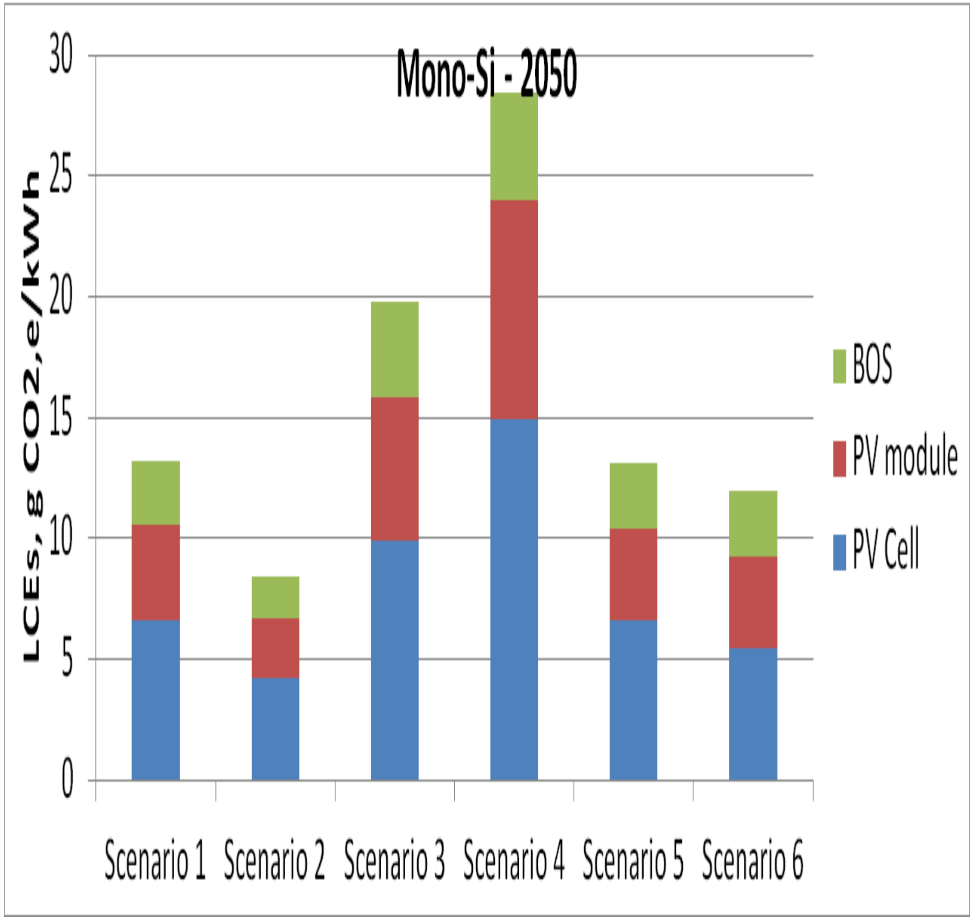
Scenario	Parameter tested	
Scenario 1: Base	As described above	
Scenario 2	Increase module efficiency by 2 percentage points every 10 years	Research is are underway to develop PV cells with higher efficiencies. For monocrystalline PV cells, currently, 16-18% efficiency at the laboratory scale is achievable. In 2050, module efficiencies of 22% for crystalline Si and 17% for CdTe is assumed.
Scenario 3	Reduce life time from 30 to 20 years	The majority of PV modules installed in the UK have not achieved the end of their life yet so there is uncertainty about PV module lifetime. Due to severe weather conditions, PV lifetime may be lower than expected.
Scenario 4	Alternate scenario for material carbon intensity and grid intensity for manufacturing location	Alternate scenario based on IEA's 4 degrees scenario
Scenario 5	PV module manufacture is in the UK	Plans are underway to build factories to assemble PV module in the UK with PV cells imported from Europe
Scenario 6	Both PV cell and PV module manufacture is UK	Factories assembling PV module will also be able to manufacture PV cells in the future

Sensitivity analysis: Mono-crystalline Si

RICARDO-AEA

The modelled change in total LCEs overtime for **mono-crystalline Si** are shown below, for each of the scenarios. The scenario exploring PV module lifetime (Scenario 3) has the biggest impact on current LCEs. In 2050, the scenario that assumes a higher carbon and grid intensity for manufacturing (Scenario 4) is most important, increasing LCE by more than 100% relative to the base case. An increase of module efficiency to 22% in 2050 would reduce LCEs by about 40%.



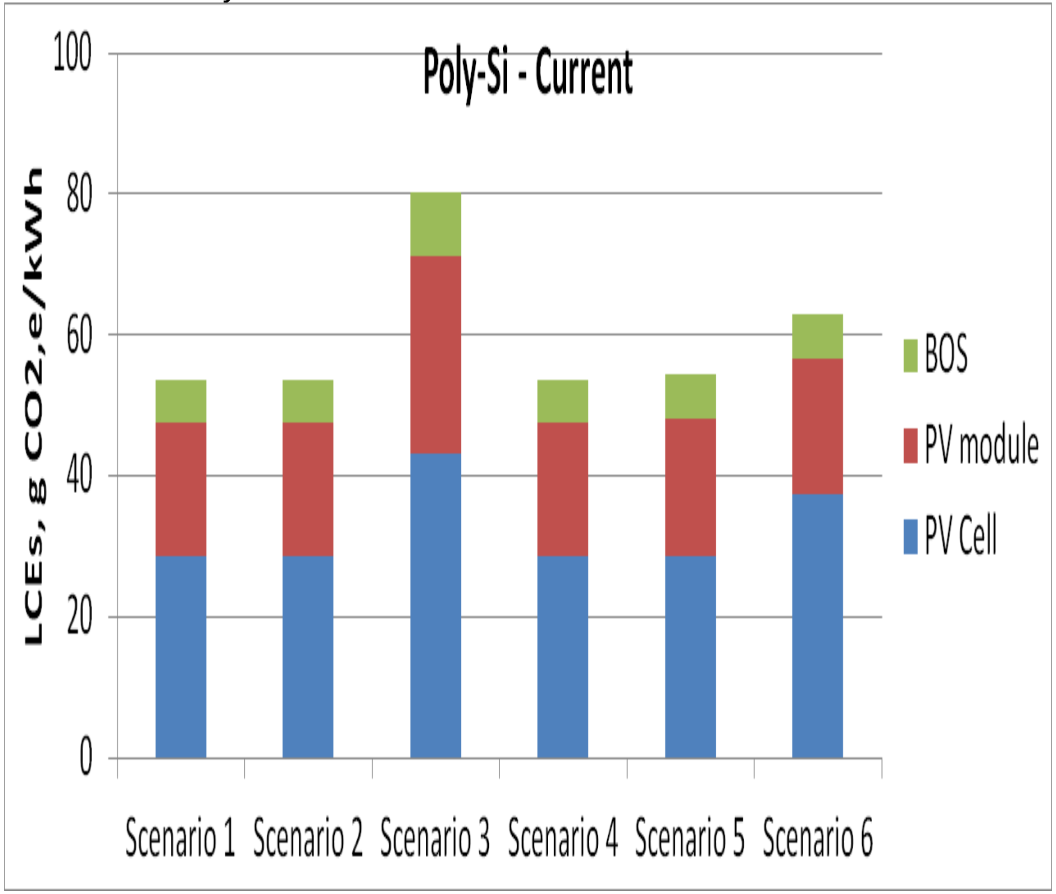


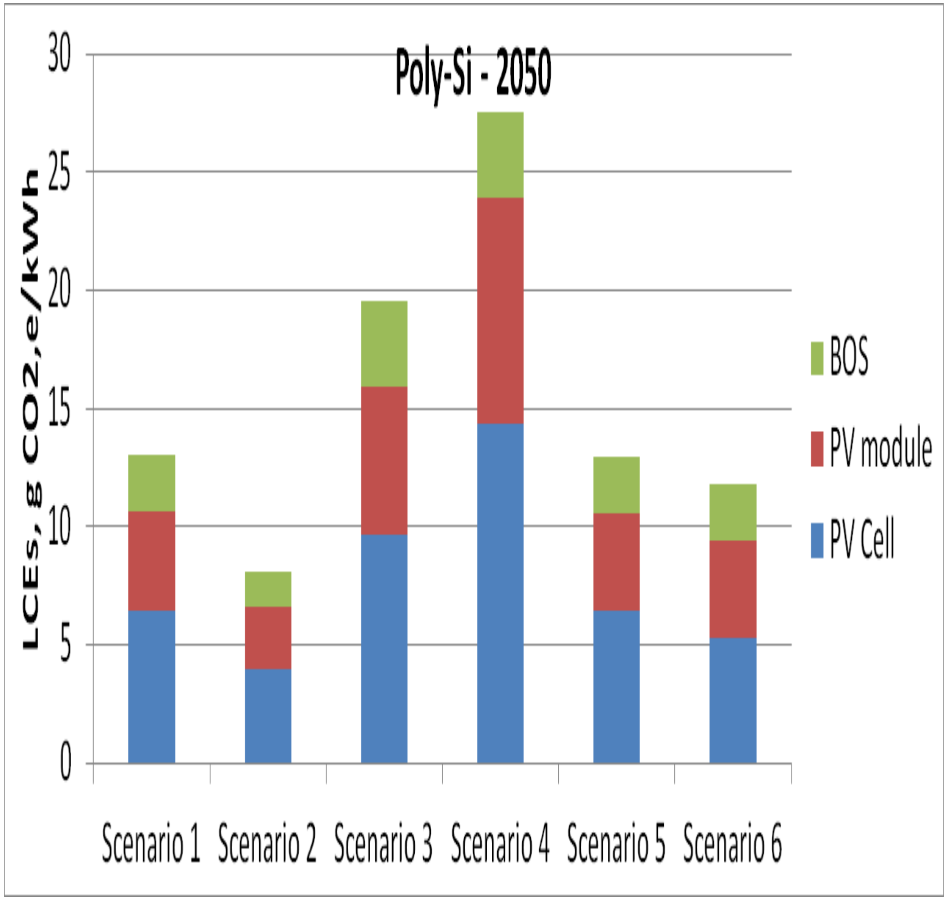
Scenario description as on slide 100

Sensitivity analysis: Poly-crystalline Si

RICARDO-AEA

The modelled change in total LCEs overtime for **poly-crystalline Si** are shown below, for each of the scenarios. Similar trends are observed as for mono-crystalline Si. The scenario exploring PV module lifetime (Scenario 3) has the biggest impact on current LCEs. In 2050, the scenario that assumes a higher carbon and grid intensity for manufacturing (Scenario 4) is most important, increasing LCE by more than 100% relative to the base case. An increase of module efficiency from 13% (as in the base scenario) to 21% in 2050 would reduce LCEs by about 40%.

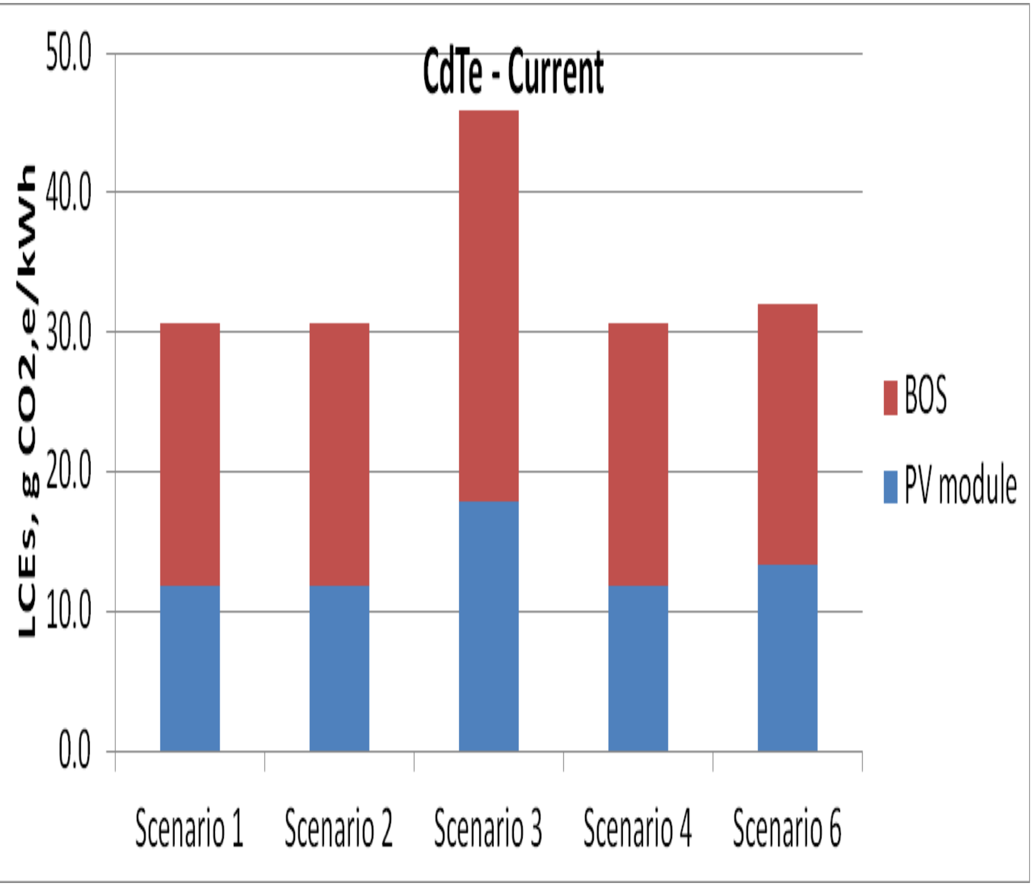


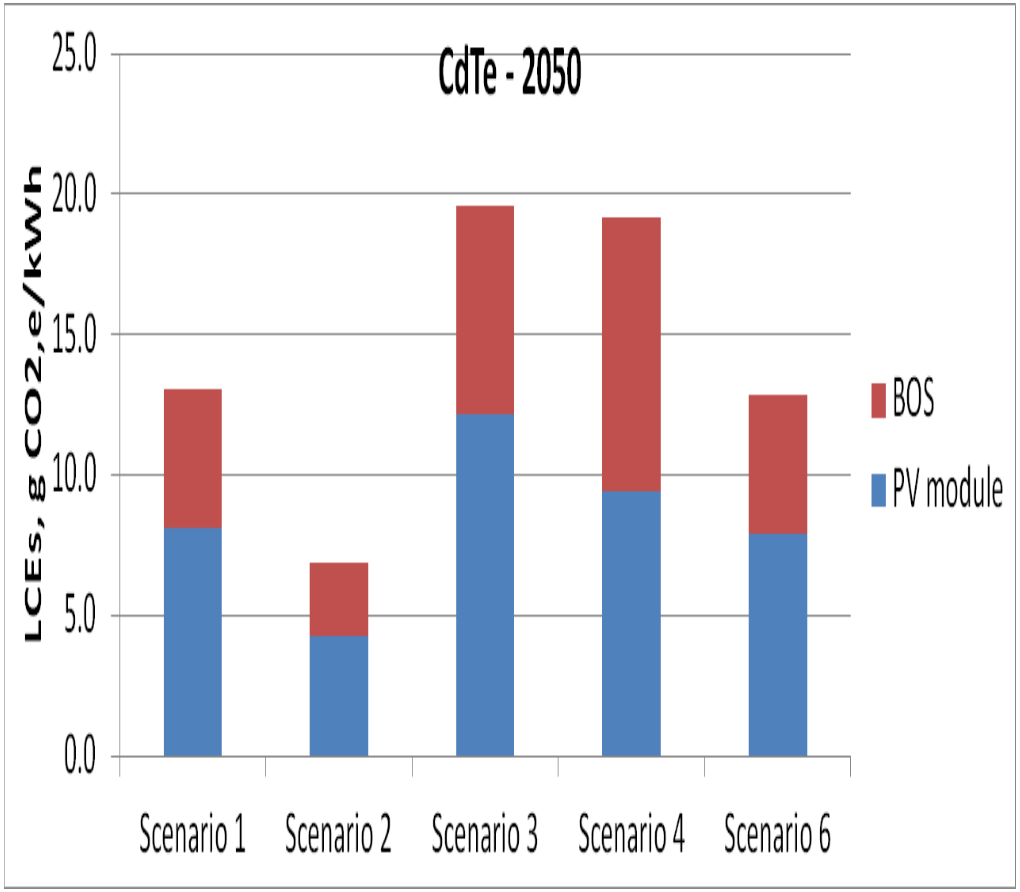


Scenario description as on slide 100

Sensitivity analysis: CdTe

The modelled change in total LCEs overtime for **CdTe** are shown below, for each of the scenarios. The scenario exploring PV module lifetime (Scenario 3) has the biggest impact on current and 2050 LCEs. In 2050, the scenario that assumes a higher carbon and grid intensity for manufacturing (Scenario 4) is also important, increasing LCE by about 50% relative to the base case. An increase of module efficiency from 9% (as in the base scenario) to 17% in 2050 would reduce LCEs by about 50%.





Scenario description as in slide 100. Scenario 5 is not considered separately for CdTe since the CdTe spreadsheet model considers PV cell and PV module manufacture as a single life cycle stage.

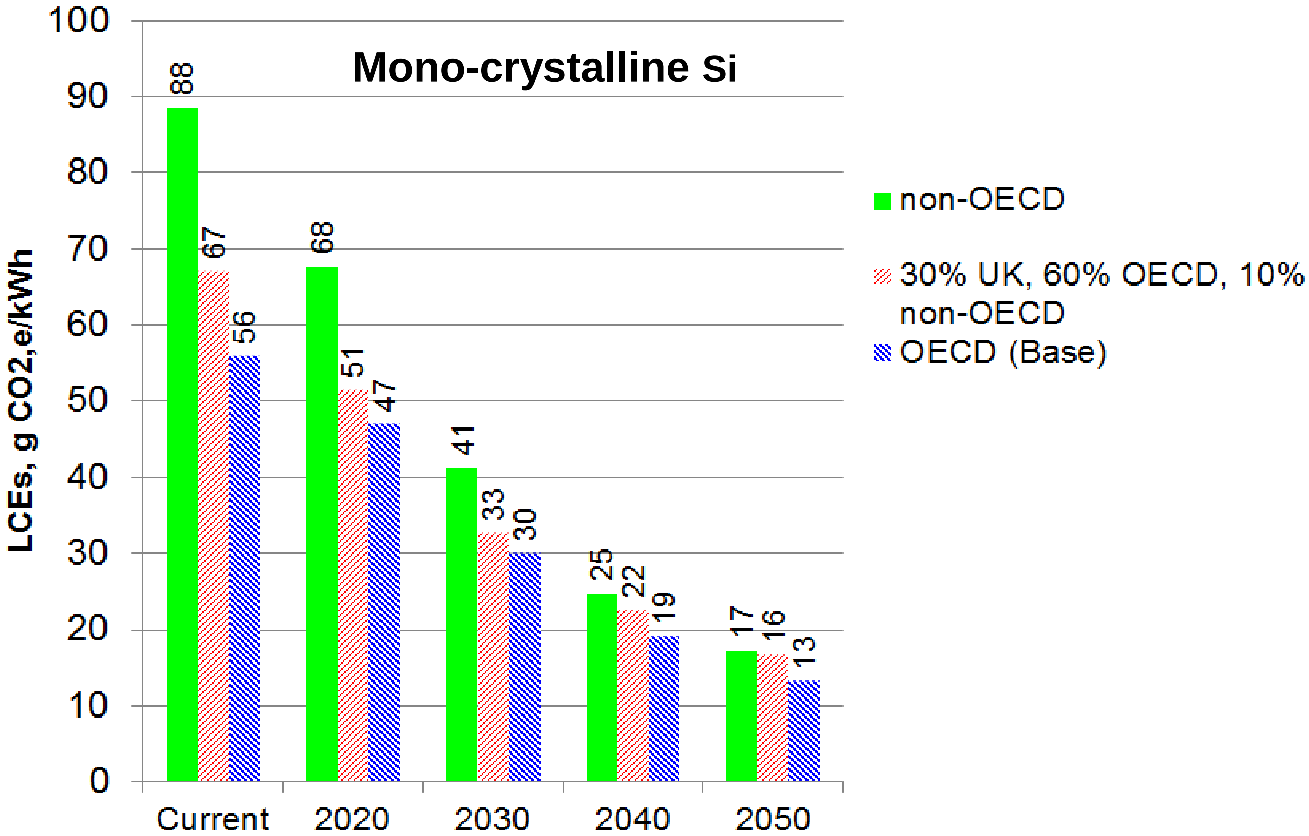
Effect of manufacturing location

RICARDO-AEA

The base scenario for the PV systems considered here assumes that all PV cell / PV module manufacturing is in OECD Europe. The figure below compares LCEs for two additional scenarios:

1. Where all manufacturing is in OECD countries (e.g. China): in this case, current LCEs increase by about 60% (about 30% in 2050) relative to the base case.
2. Where 30% of manufacturing is in the UK, 10% in non-OECD countries and the rest in OECD Europe: in this case, LCEs increase by about 20% (about 25% in 2050) relative to the base case.

It should be noted that the scenarios shown below are generated under the 2º scenario and so LCEs from the three scenarios shown below are expected to converge by 2050 as shown. This could look different for the 4º scenario.



Conclusions – Solar PV

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- For the base scenario, the total life cycle emissions are respectively 56, 53 and 31 g $CO_{2,e}$/kWh for mono-crystalline, poly-crystalline Si and CdTe resp. This is in agreement with the range of figures reported in the literature.

- For Si-based PV systems, LCEs could be reduced by 75% by 2050 while or CdTe, LCEs could be reduced by 60% by 2050.

- Most LCEs are attributed to the manufacturing stage of the lifecycle. Since the base scenario assumes manufacturing outside the UK, more than 90% of LCEs, currently and in 2050, are non-UK emissions.

- The key factors influencing LCEs now and in the future are the module technology parameters (efficiency, life time) and the carbon intensity of material production and the electricity grid.

- If the alternate scenario (based on IEA ETP 4DS) is considered instead of the base 2DS scenario, LCE in 2050 increase by 115% for Si-based PV modules and by 50% for CdTe thin film PV modules in comparison to the base case LCEs in 2050.

- The location of PV cell manufacturing has a more pronounced effect on total LCEs than the location of PV module manufacturing. PV cell manufacturing in the UK will lead to higher LCEs currently but will lead to slightly lower LCEs in 2050. Currently and in the future, PV module assembly / manufacture in the UK will not significantly impact LCEs. However, by 2020, PV cell manufacture in the UK will lead to a reduction in LCEs.

Comparison of technologies in the power sector

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Power sector – technology comparison

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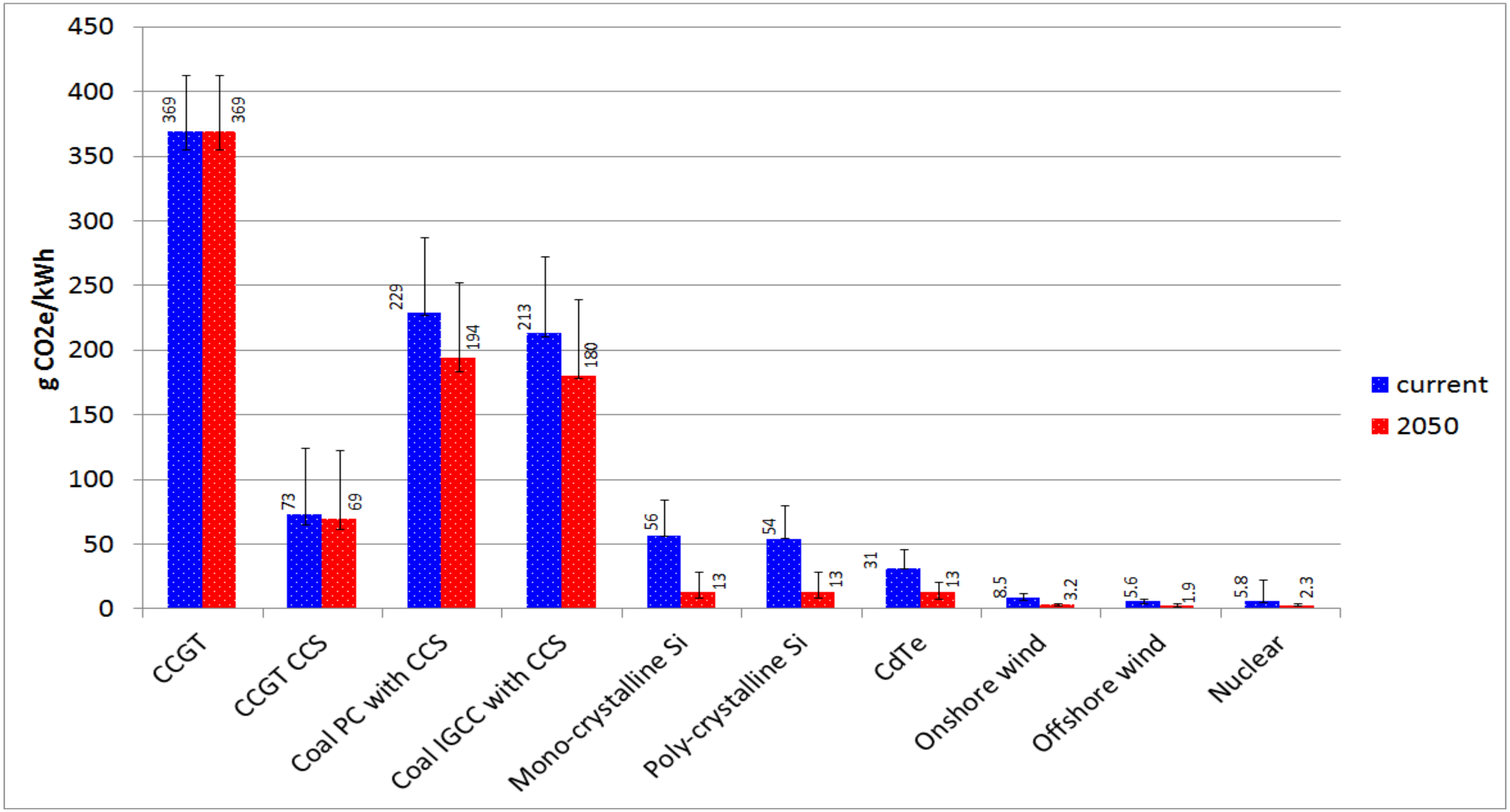
The chart below compares the LCEs of each of the technologies under the respective base case assumptions. The change in emissions between current year and 2050 is also shown. The estimates are considered representative of the broad literature, but may differ from specific studies due to differences in assumptions.



Overall, higher CO_2 / GHG savings are expected to result by 2050 from renewables than from CCS, under the base cases assumptions. For solar PV, wind and nuclear, savings between 50% and 70% are expected in 2050 relative to the current year.

Share of UK emissions

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The table below shows the range for UK and non-UK emissions for each of the technologies based on best and worst case scenario. It is seen that for fossil fuel technologies, most current LCEs are located within the UK while for renewable technologies and nuclear a significant share of current LCEs are located outside the UK. In 2050, UK-based LCEs for fossil fuel technologies (including CCS) will increase (assuming that no improvements in power generation and CO_2 capture efficiency are achieved).

Technology	Current LCEs		2050 LCEs	
	% LCEs from the UK	% LCEs outside the UK	% LCEs from the UK	% LCEs outside the UK
CCGT / no CCS	84%	84%	97%	97%
CCGT with CCS	38%	36%	83%	76%
PC with CCS	61% - 69%	31% - 39%	67 %– 75%	25% - 33%
IGCC with CCS	52% - 60%	40% - 48%	59% - 68%	32% - 41%
Nuclear	34% - 58%	42% - 66%	24% - 41%	59% - 76%
Onshore wind	32% - 33%	67% - 68%	38% - 45%	55% - 62%
Offshore wind	42% - 45%	55% - 58%	53% - 57%	43% - 47%
Monocrystalline Si	13-15%	85% - 87%	20%	80%
Polycrystalline Si	11%	89%	18%	82%
CdTe PV	61%	39%	28%	72%

The Residential Sector

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The heat pump and gas boiler life cycles

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The heat pump life cycle stages

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Current and future LCEs were estimated for air-source and ground-source heat pumps, and compared with the LCEs for gas boilers. The key stages in the heat pump life cycle are shown below.

Manufacture

- Raw material requirements
- Energy requirements
- Refrigerant type and leakage during manufacture

Transport

- Transport of raw materials to manufacturing site
- Transport of heat pump to installation site
- Train, lorry and van transport

System installation

- Heat pump installation
- Raw material requirements
- Energy requirements

Operation

- Electricity (UK grid intensity)
- Refrigerant top-up
- Refrigerant leakage during operation

Disposal

- Raw material recycling
- Energy requirement

Current emission hotspots in the heat pump life cycle

The literature is in agreement that currently most LCEs for heat pumps arise from the operational stage. This is due to both electricity consumption and refrigerant leakage.

Currently, most of these operational emissions are due to electricity consumption. However, as the UK grid becomes decarbonised in 2050, most of the operational emissions could be due to refrigerant leakage during operation. The most common refrigerants currently used in heat pumps are the two hydrofluorcarbons (HFCs): R134a (1,1,1,2-tetrafluorethane, CH2FCF3) and R410a (mixture of difluoromethane, CH_2F_2 and pentafluoroethane, CHF_2CF_3).

	Manufacture	Transport	Installation	Operation	Disposal
ASHP:	B	B	B	A	B
GSHP:	C	C	B	A	C

A: Dominant
B: Significant
C: Negligible

Installation emissions are more significant for GSHPs than for ASHPs due to the digging and construction work involved in installing the heat collector underground.

Geographical factors

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- As the dominant contributor to LCEs for both the heat pump and gas boiler life cycles is the operational stage, most emissions from both of these technologies will currently be based in the UK.

- The key refrigerants used in heat pumps currently are R134a and R410a. These are manufactured in the UK and so emissions from this part of the life cycle, as well as leakage during operation and disposal, will arise in the UK. The carbon footprint for the different refrigerants as well as the GWP are shown in the table below.

- Hydrofluorcarbons (HFCs) such as R134a and R410a have zero ozone-depleting potential but a very high global warming potential (GWP). Currently there is no legislation which bans the use HFCs but it is expected that such legislation will be in place in the future. Carbon dioxide refrigerant (R744) heat pump provide an opportunity to reduce LCEs, as the GWP is much lower than for HFCs. However, CO_2 heat pumps have lower COP in comparison to heat pumps with conventional refrigerants and so they are still in the early commercialisation phase (mainly trans-critical cycle heat pumps) but are expected to capture a larger segment of the market in the future due to their environmental benefits.

- Currently the key manufacturers supplying heat pumps to the UK are based in the EU and the US. These include Dimplex (Germany) and NIBE (Sweden). It is likely that production will remain in Europe as market expands. Other key markets are North America, Japan, China.

- Other factors which could influence LCEs include size reduction (c.f. gas engine driven heat pumps), refrigerant charge reduction and minimising leakage through more robust system components.

- Gas boilers are assumed to be manufactured in the UK

Refrigerant	GWP	$kgCO_2e/kg$
R-134a	1430	49
R-410a	2088	173
R744	1	1.6

Base case scenario assumptions

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The technology characteristics and base case scenario assumptions are summarised below. The base scenario for carbon and grid intensity (based on the IEA ETP 2 scenario) is assumed. The manufacturing location (and source of raw materials used in manufacturing) is assumed to be OECD Europe as currently is the case and is the assumption in recent UK-based studies. For this study, however, the grid intensity is averaged over the lifetime of the heat pump.

Parameter	ASHP	GSHP	Gas boiler
Performance parameters	As below	As below	As below
Manufacturing location	OECD Europe	OECD Europe	UK
Source of raw materials	OECD Europe	OECD Europe	UK
Material carbon intensity	IEA 2DS	IEA 2DS	IEA 2DS
Grid intensity	IEA 2DS	IEA 2DS	IEA 2DS
Refrigerant type	R-134a	R134-a	NA
Refrigerant leakage – manufacture	3%	3%	NA
Refrigerant leakage, per annum	6%	6%	
Disposal leakage	20%	20%	NA

R134a is the most common hydrofluorcarbon (HFC) used in heat pumps and so this is assumed for the base case scenario. Typical refrigerant leakage rates for the manufacture, operation and disposal stages are assumed as shown in the table based on based on recent studies.

Parameter	ASHP	GSHP	Gas boiler
Size, kW	10	10	10
Lifetime, years	20	20	20
Efficiency	NA	AN	90%
Seasonal performance factor (SPF), current	2.5	3.15	NA
SPF, 2050	3.5	3.95	NA
Load factor	14%	14%	2000 hours/year

The heat pump operational parameters are based on CCC modelling. These are shown in the table to the left.

Comparison to previous studies

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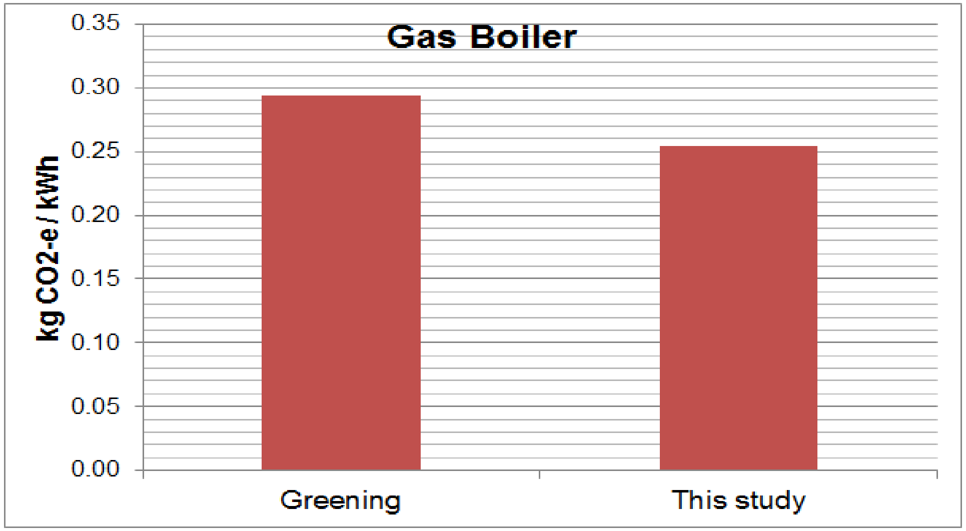
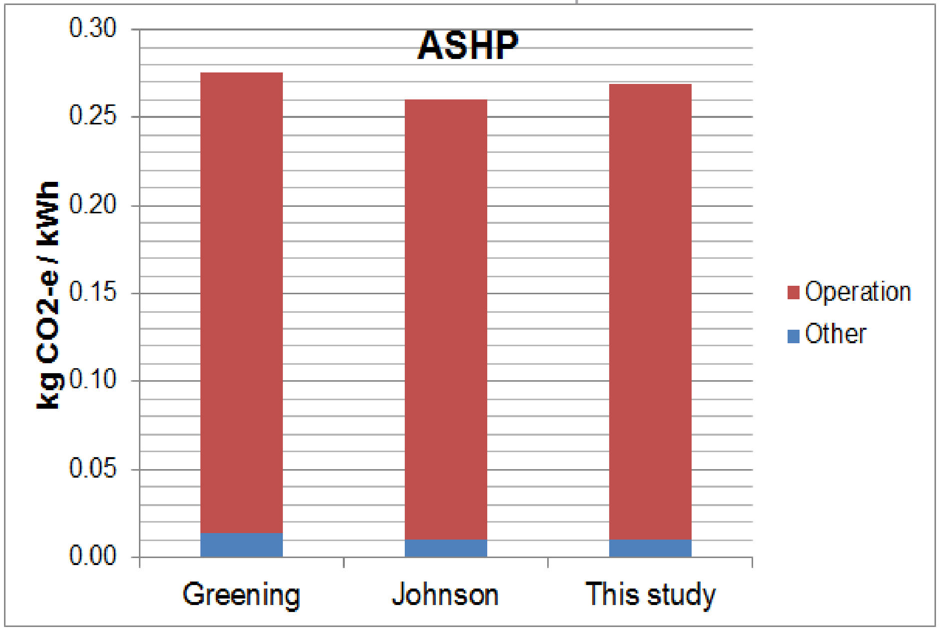
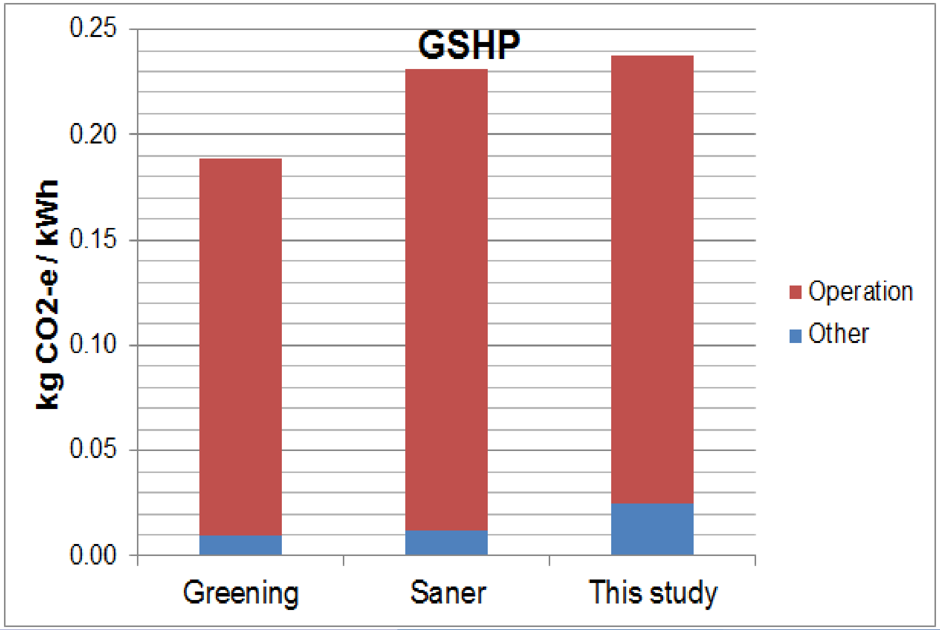
The spreadsheet calculation tool was run for the base scenario for the ASHP, the GSHP and the gas boiler. The results are compared to the literature as shown. For comparison purposes, the results compared here assume the current UK grid and that the UK grid intensity remains fixed over the lifetime of the heat pump (as usually assumed in the literature).
It is seen that most LCEs result from the operational phase. ASHP has higher LCEs than GSHP due to the lower SPF.
The study by Greening and Azapagic reports 6% savings for the ASHP in comparison to the gas boiler. For the GSHP, the savings in comparison to the counterfactual are 36%.



Most boiler LCEs are attributed to the operational phase including gas combustion (89%) and upstream emissions from the natural gas fuel cycle (including methane leakage from gas distribution, assuming 0.57% leakage rate). The study by Greening does not state the leakage rate but states that combustion emissions are 220 g CO2,e/kWh

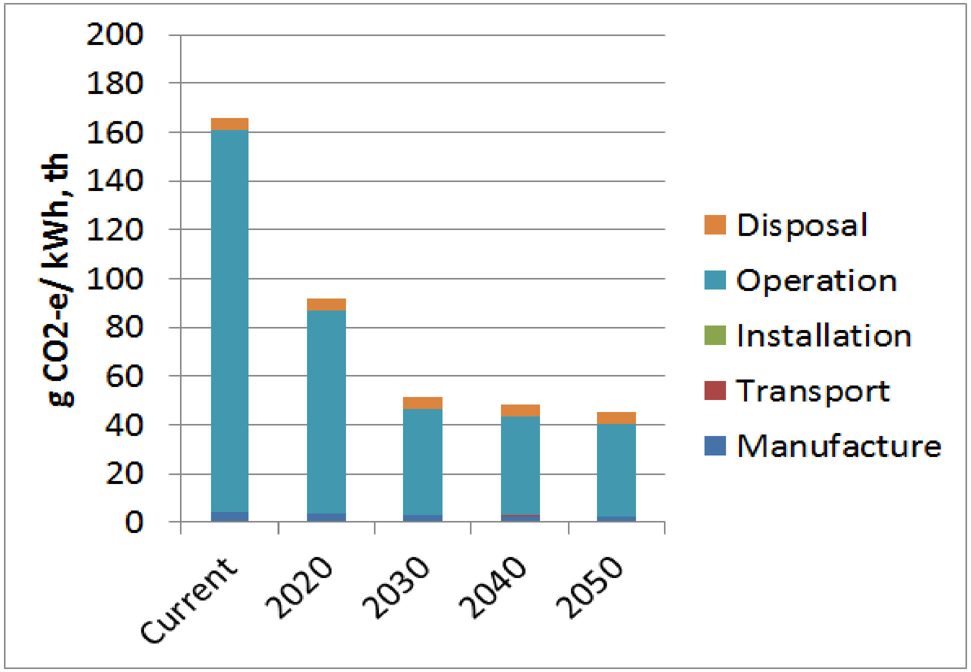




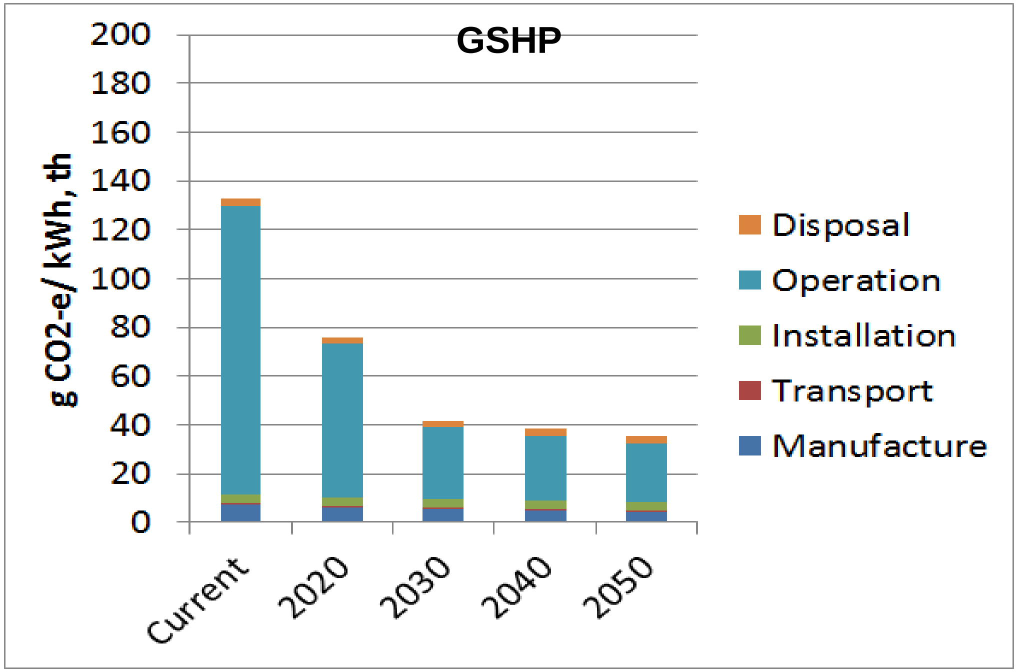
Base scenario (current and future LCEs)

Current and future LCEs are shown for the base scenario below. The results shown below account for grid decarbonisation and so the electricity EF is averaged over the life time of the heat pump. As a result, the grid intensity used in estimating operational LCEs over the life time of the heat pump (current to 2030) is 25-45% lower than the current grid intensity for the UK.

It is shown below that most LCEs are attributed to the operational phase (both electricity consumption and refrigerant leakage). Due to the high-GWP refrigerant, the share of operational emissions is still high in 2050.



By 2050, overall LCEs reduce from 166 Kg $CO_{2,e}$/ kWh to 46 g $CO_{2,e}$/ kWh (72% reduction)



By 2050, overall LCEs reduce from 133 Kg $CO_{2,e}$/ kWh to 37 g $CO_{2,e}$/ kWh (72% reduction)

Gas boiler

Emissions from the gas boiler remain fixed at 254 g/kWh to 2050. Of the gas boiler operational emission, 11% are attributable to the upstream gas cycle and the rest to combustion. Upstream emissions from the gas fuel cycle are estimated using the base case scenario assumptions listed on slide 49.

Base scenario: refrigerant LCEs

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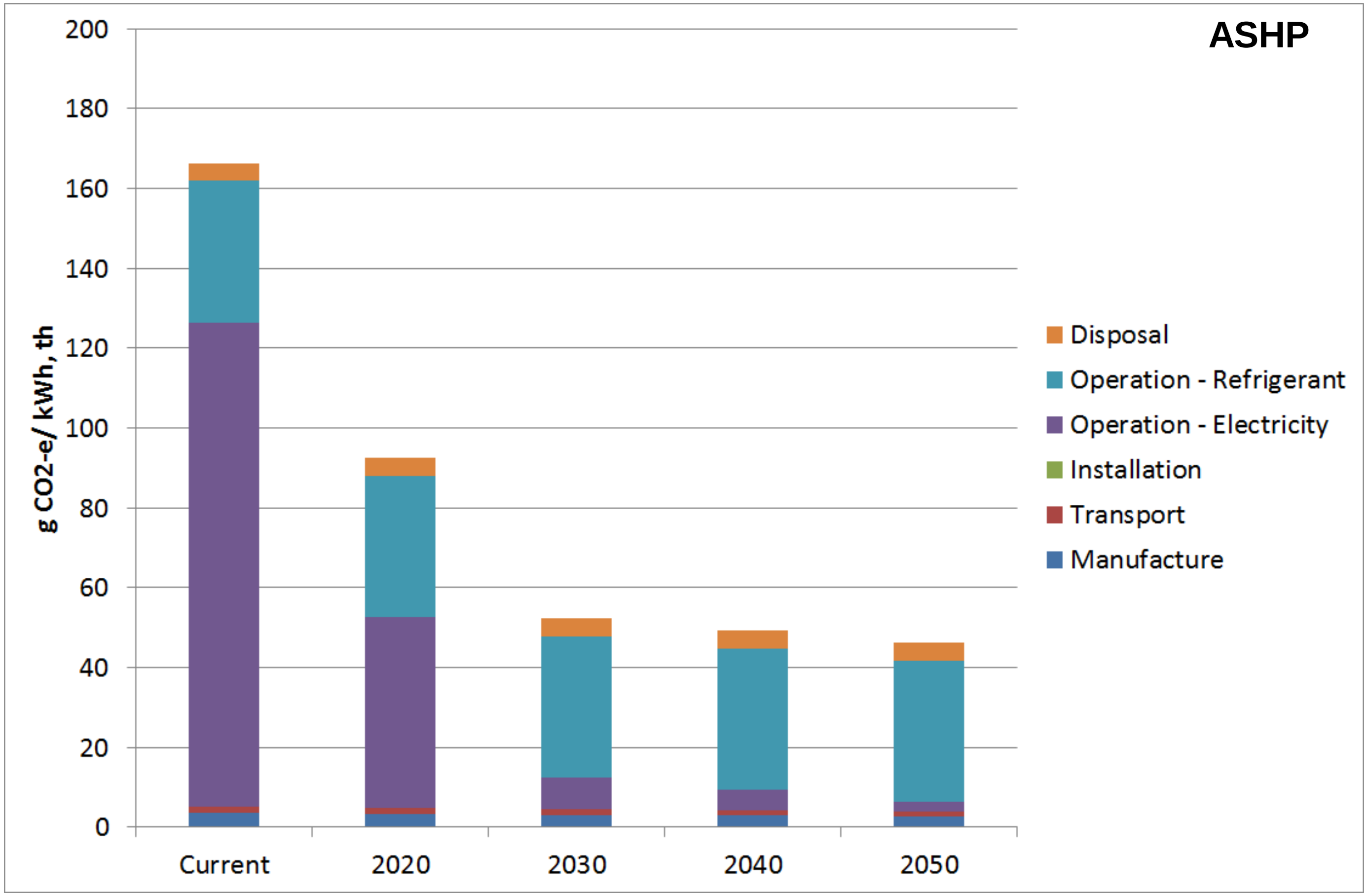
The figure below shows LCEs for ASHP with operational emissions broken down by emissions from ‘electricity consumption’ and from ‘refrigerant leakage and manufacturing’. Heat pump refrigerant contributes a significant share of operational emissions (22% currently and 95% in 2050) particularly due to leakage during operation.

Currently, most operational LCEs result from electricity consumption. As the grid is decarbonised in 2050 and assuming that refrigerant leakage remains at current levels, most operational emissions result from the refrigerant.



Location of emissions (Base scenario)

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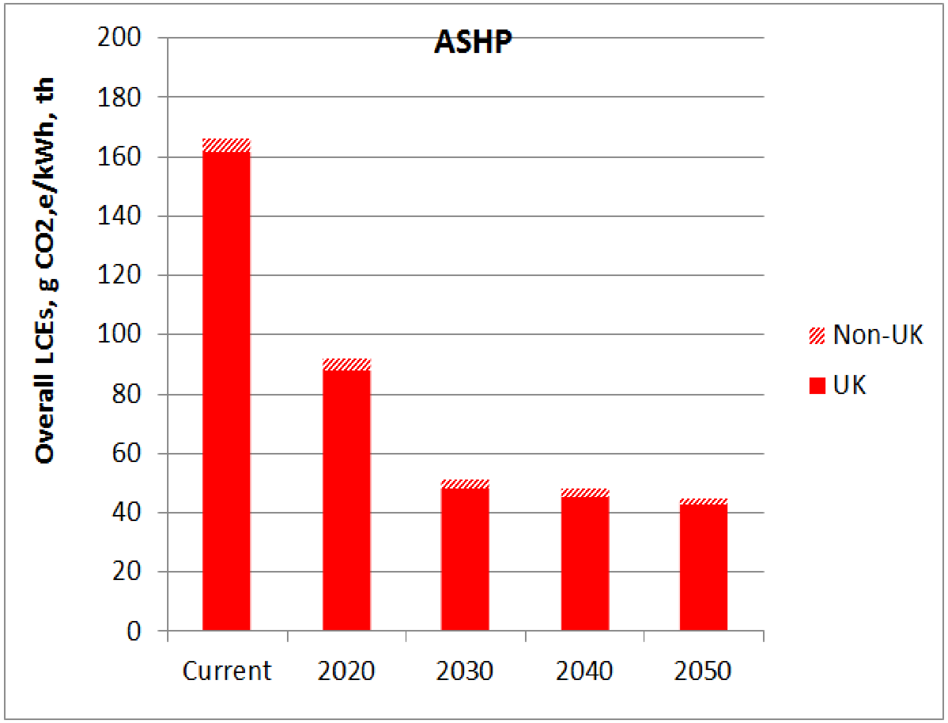
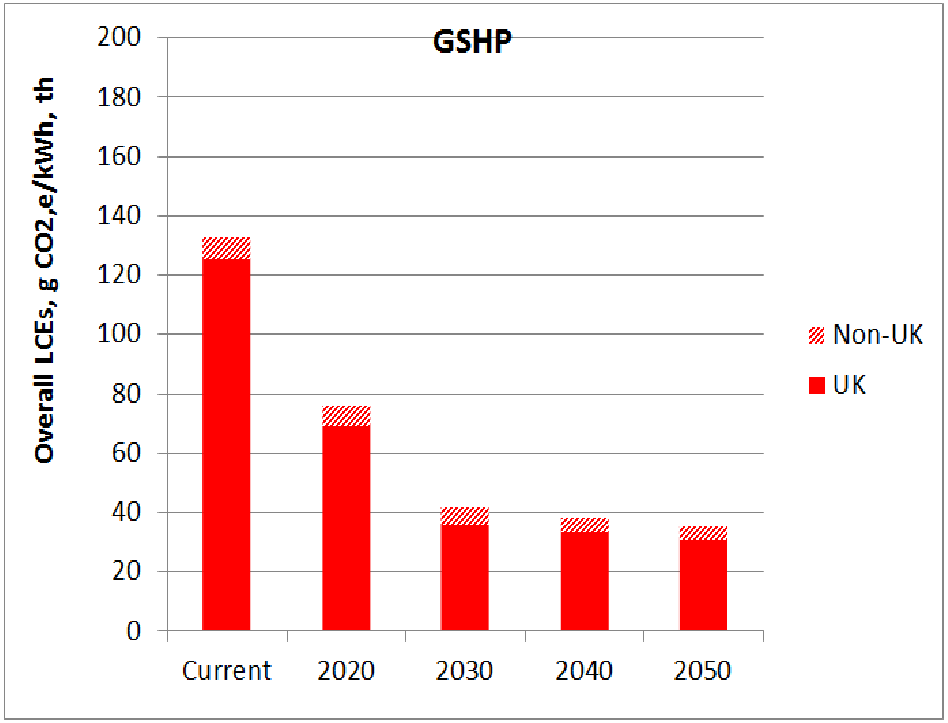
The share of UK emissions is shown in the figure below. Operational emissions from both electricity and refrigerant leakage are UK emissions and, despite the decarbonisation of the grid in 2050, most LCEs are still located in the UK as a result of refrigerant leakage. UK-based emissions for the GSHP are slightly lower due to the higher share of installation emissions which are negligible for the ASHP.





Sensitivity analysis: scenario definitions

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Several scenarios were tested as shown in the table below. These are compared to the base scenario in the following slides.

Scenario	Parameter tested	
Scenario 1: Base	As above	
Scenario 2	Replacing refrigerant R134a by CO_2 (R744)	This is not commercially deployed on a large scale yet but is expected to be in the future (by 2030). R744 has a GWP of 1 and has lower carbon footprint than HFCs.
Scenario 3	Reduction of operational leakage rate by 50% below current rates by 2050	Efforts are underway to manufacture tighter systems with lower leakage rates.
Scenario 4	Reduction of heat pump size by 25% in 2050	It is possible that heat pumps in the future (e.g. CO_2 heat pumps) will be smaller in size and will require less raw material for manufacturing
Scenario 5	Reduced COP (assuming SPF of 2.2 for the ASHP and 2.4 for the GSHP fixed to 2050)	Based on the EST field trials (http://www.heatpumps.org.uk/PdfFiles/TheEnergySavingTrust-GettingWarmerAFieldTrialOfHeatPumps.pdf)
Scenario 6	Alternate material carbon and grid intensity scenario (based on IEA's 4 degrees scenario)	High carbon intensity of production will affect manufacturing while high UK grid intensity will affect operational stage
Scenario 7	Combination of scenarios 2, 3 and 4	Best case scenario with R744 as the refrigerant, with lower leakage, improved SPF and smaller heat pump size
Scenario 8	Worst case scenario: Alternate material carbon and grid intensity scenario (based on IEA's 4 degrees scenario) – Worst case scenario	High carbon intensity of production will affect manufacturing while high UK grid intensity will affect operational stage

Sensitivity analysis: Results

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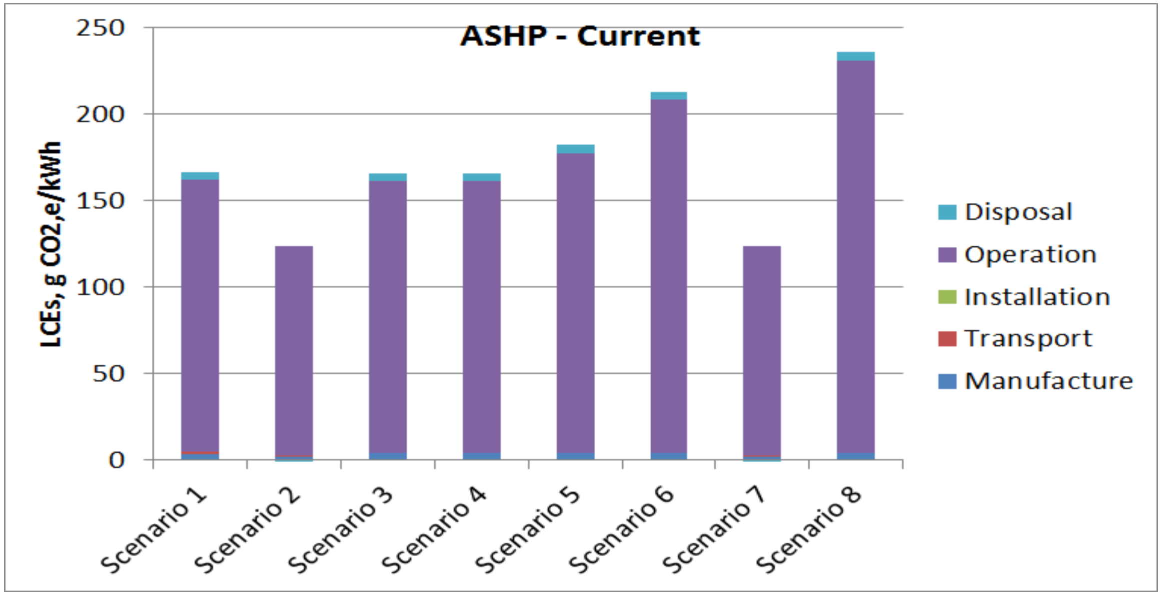

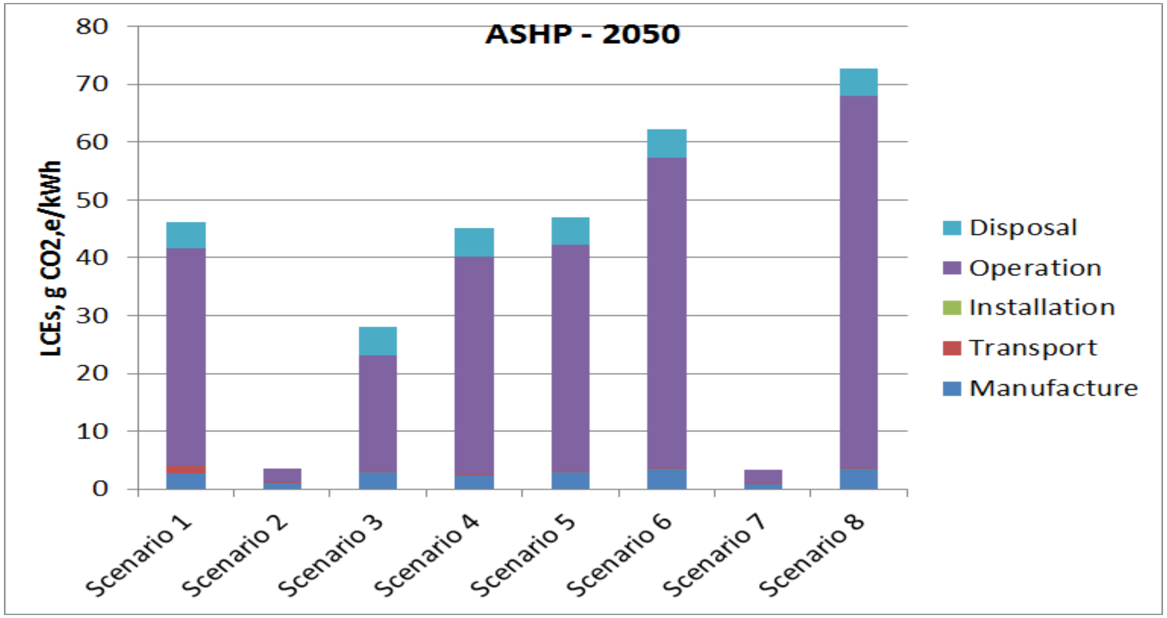

- Replacing current conventional refrigerants by CO_2 (R744) refrigerant (Scenario 2) leads to highest reduction in LCE now (by 25%) and in the future (by 90%)
- Reducing operational leakage rate to 50% below current levels by 2050 (Scenario 3) reduces LCEs by 40% in 2050.
- Size reduction (Scenario 4) has minimal effect on LCEs now and in 2050
- A reduction in the SPF to 2.2 (Scenario 5), increases LCEs by 10% (current) and 2% in 2050.
- An alternate scenario for material carbon intensity and grid intensity (following the IEA's 4DS) increases LCEs by 30-35%.
- In a worst case scenario where material carbon intensity and grid intensity follow the IEA's 4DS and the COP is reduced to 2.2, LCEs increase by 30-40%.
- For the best case scenario (see previous slide for scenario 7), the controlling parameter leading to reduction on LCEs is the change of refrigerant from R134a to R744 (CO_2 refrigerant). This is because the effect of leakage rate becomes insignificant when CO_2 is the refrigerant.

Scenario description as shown on slide 119

Sensitivity analysis: Results

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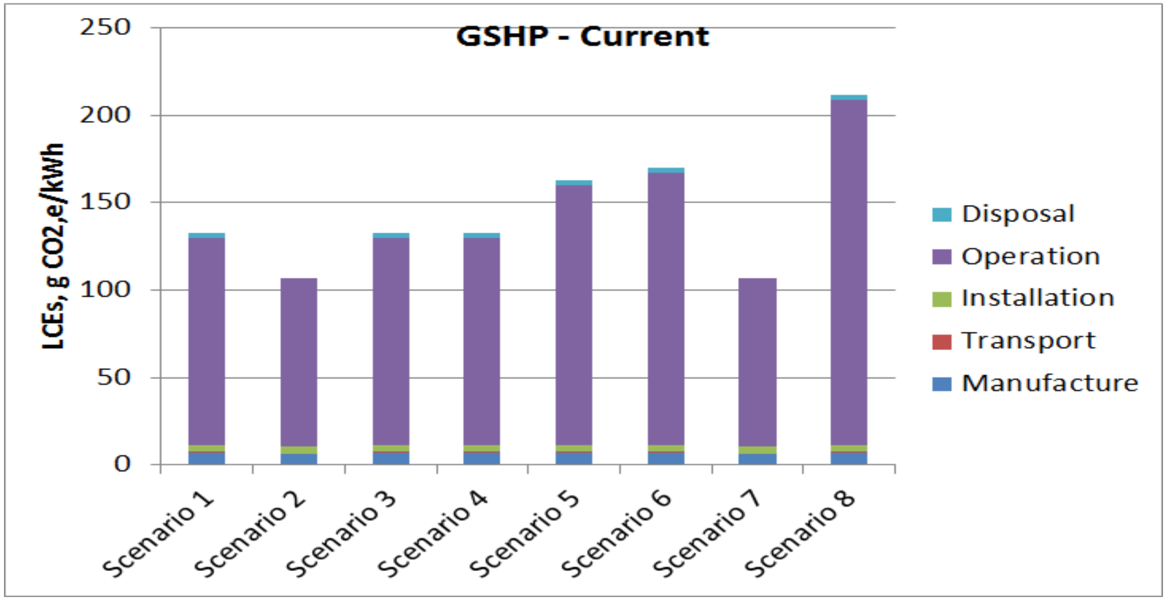

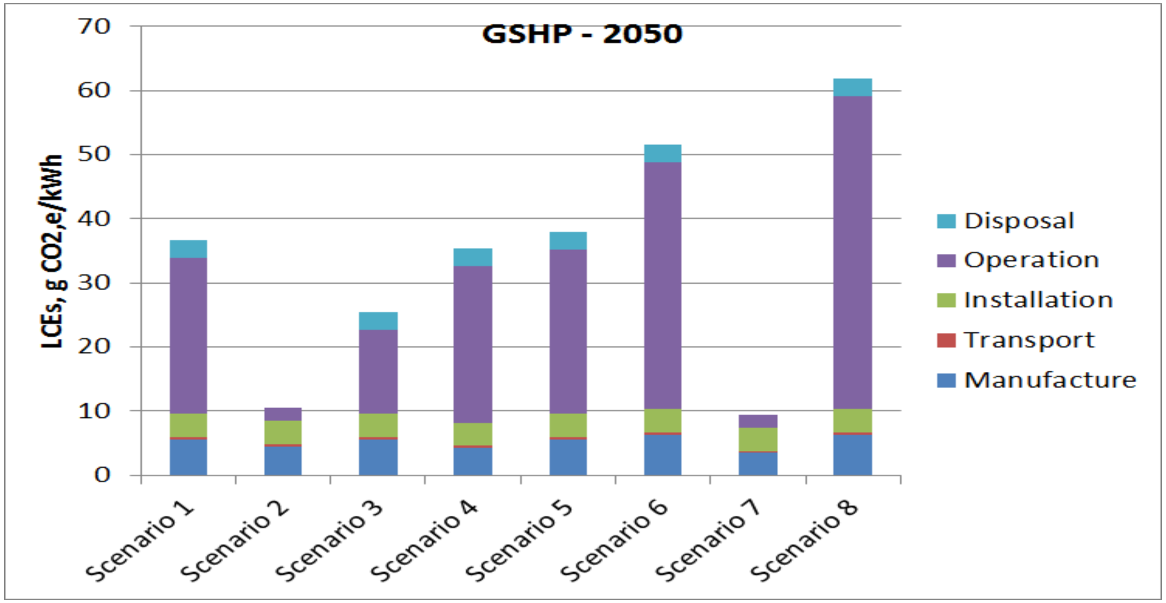

- Similar trends are observed for the GSHP as for the ASHP.
- Replacing current conventional refrigerants by CO_2 (R744) refrigerant (Scenario 2) leads to highest reduction in LCE now (by 20%) and in the future (by 65%). The effect of the low-GWP refrigerant is slightly reduced by the fact that GSHP is associated with higher shares of non-use LCEs in comparison to ASHP.
- Reducing operational leakage rate to 50% below current levels by 2050 (Scenario 3) reduces LCEs by 28% in 2050.
- Size reduction has minimal effect now and in 2050 on LCEs
- A reduction in the SPF to 2.4 (Scenario 5), increases LCEs by 20% (current) and 5% in 2050.
- An alternate scenario for material carbon intensity and grid intensity (following the IEA's 4DS) increases LCEs by 28-38%.
- In a worst case scenario where material carbon intensity and grid intensity follow the IEA's 4DS and the COP is reduced to 2.4, LCEs increase by 60-65%.
- For the best case scenario (see slide 119 for scenario 7), the controlling parameter leading to reduction on LCEs is the change of refrigerant from R134a to R744 (CO_2 refrigerant). This is because the effect of leakage rate becomes insignificant when CO_2 is the refrigerant.

Scenario description as shown on slide 119

Conclusions

- Current LCEs from heat pumps are around 170 g $CO_{2,e}$/kWh for ASHP and around 135 g $CO_{2,e}$/kWh for a GSHP. These figures assume an averaging of the grid intensity over the life time of the heat pump (see slide a53 under Fuels).

- Current LCEs from gas boilers are around 260 g $CO_{2,e}$/kWh. Current LCE savings for heat pumps in comparison to the gas boiler are 35% for ASHP and about 45% for GSHP. Based on our base scenario analysis, savings could reach expected to reach more than 80% by 2050 for both types of heat pumps.

- Currently , for both types of heat pumps, more than 90% of LCEs are attributed to the operational phase. Currently, about 20% of the operational phase emissions are caused by the refrigerant (both leakage and life cycle emissions) but this could rise to 95% in 2050.

- In 2050, while the grid is decarbonised, operational emissions will still be dominant due to refrigerant leakage. In order to reduce LCEs from heat pumps in 2050, refrigerant emissions need to be reduced by replacing conventional HFCs with low-GWP refrigerants (such as R744) and by also reducing refrigerant leakage rates during operation.

- In the base case scenario for both ASHP and GSHP, despite the decarbonisation of the grid, the majority of emission in 2050 are UK-based. This is due to refrigerant leakage during the operation of the heat pump.

- The sensitivity analysis shows that the key factors which could influence current and future LCEs are the UK grid intensity, type of refrigerant, refrigerant leakage rate and COP. In 2050, the influence of leakage rate and the technology COP on overall LCEs become secondary to (1) the influence of replacing conventional refrigerants by low-GWP refrigerants such as R744 and / or (2) the influence of decarbonising the grid.

- Our analysis shows that future LCE could be in the range 10-120 g $CO_{2,e}$ /kWh in 2030 and 5-70 g $CO_{2,e}$/kWh in 2050.

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Solid wall insulation

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The life cycle stages

A brief study was undertaken to estimate LCEs from solid wall insulation. The key life cycle stages for solid wall insulation are the insulation manufacture, material transport, installation and disposal. The manufacture stage is the main contributor to overall LCEs.

Insulation manufacture → **Material transport** → **Installation** → **Disposal**

The Functional Unit

With respect to thermal insulation products, the thermal resistance (m^2.K/W) has been generally accepted as the operational functional unit. It gives information about the amount of insulation material required to perform a certain thermal resistance over the insulation lifetime. The mass of the wall is related to resistance by the equation

Mass of insulation (kg) = Resistance (m^2.K/W) × Conductivity (W/m.K) × Density (kg/m^3) × Area (m^2)

Typically, the mass of the wall for a resistance of 1 m^2.K/W and a wall area of 1 m^2 is estimated and used as the functional unit.

The British Research Establishment (BRE) defines the functional unit for solid wall insulation as ‘1 m^2 of insulation with sufficient thickness to provide a thermal resistance value of 3 m^2K/W (*heat transfer coefficient, U = 0.33 W/m^2.K*), equivalent to approximately 100mm of insulation with a conductivity (k value) of 0.034 W/m.K ‘. A functional units in kg of material can be calculated based on the density of the insulation material used.

Solid wall insulation LCEs in the literature

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While there are many studies reporting the embodied energy and life cycle emissions associated with the manufacture of insulation materials, there are limited studies in the literature on LCEs from solid wall insulation (i.e. the full life cycle including installation and disposal).

Embodied energy and LCEs from different insulation materials are shown in the table below. Values reported by Anders et al. are per kg functional unit (corresponding to 1 m^2.K/W and 1 m^2 of wall insulation (1.18 kg for rockwool, 1.28 for paper wool and 1.26 for flax).

Material	Embodied energy (MJ/kg)	LCEs, kg $CO_{2,e}$/ kg			
		ICE database	Anders et al., 2004	Reference 1*	Reference 2**
Rockwool	16.8	1.05	1.45	-	-
Mineral wool	16.6	1.2	-	-	-
Paper wool	20.2	0.63	0.71	-	-
Glass wool	28	1.35	-	-	-
Polystyrene	109	3.4	-	2.9	3.6
Flax	39.5	1.7	2.4	-	-

* Reference 1: http://www.climatedec.com/Documents/decl/CD215.pdf (Life cycle analysis undertaken by Sirap Insulation in Italy
This reference reports 81 kg CO_2/m^3 of polystyrene panel.
** http://gryphon.environdec.com/data/files/6/7771/epde34e.pdf. (Life cycle analysis on polystyrene from recycled polymer by LAPE S.r.l).

In general, most studies conclude that the overall impacts are dominated by the insulation material production process (more than 97% of total LCEs)

Assumptions and base case scenario

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Selected insulation materials

The insulation materials selected for the present analysis are compared in the table below.

Parameter	Rockwool	Polystyrene
Brief description	The oldest type of insulation product on the market today.	Favoured by the building industry for its versatility and ease of use. It is robust and has been shown to retain its performance over 40 years.
Conductivity, W/m.K	0.037	0.03
Density, kg/m^3	35	28
Heat transfer coefficient, U, $W/m^2.K$	0.33	0.33
Kg / m^2 of wall*	4.4	2.8

* This is used to estimate total LCEs (kg CO2) per m2 of insulation panel area.

Base Case scenario

The base case scenario assumptions are summarised below. The manufacturing location (and source of raw materials used in manufacturing) is assumed to be the UK.

Parameter	Rockwool	Polystyrene
Manufacturing location	UK	UK
Source of raw materials	UK	UK
Material carbon intensity and grid intensity	IEA 2DS	IEA 2DS

Base case scenario results

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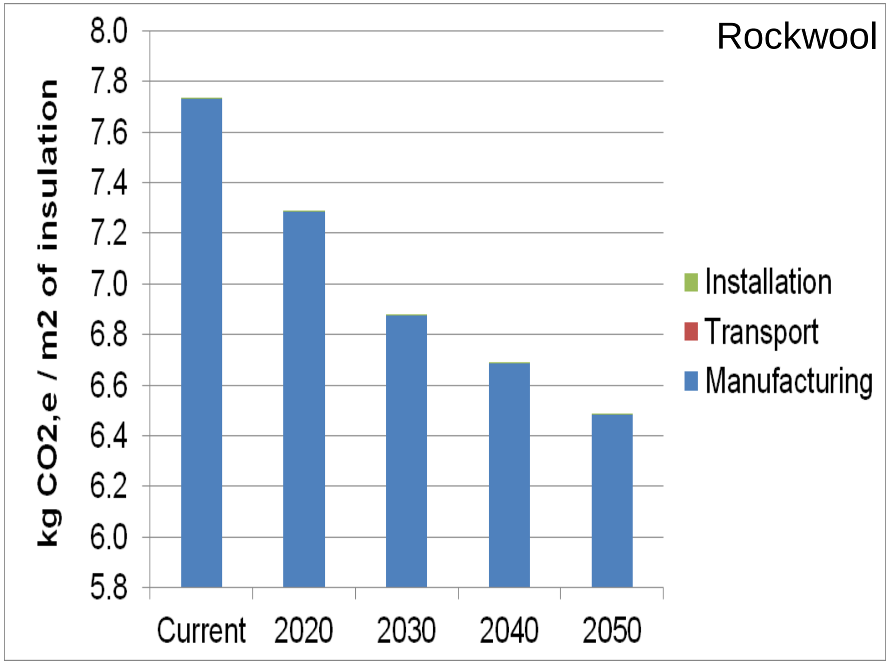
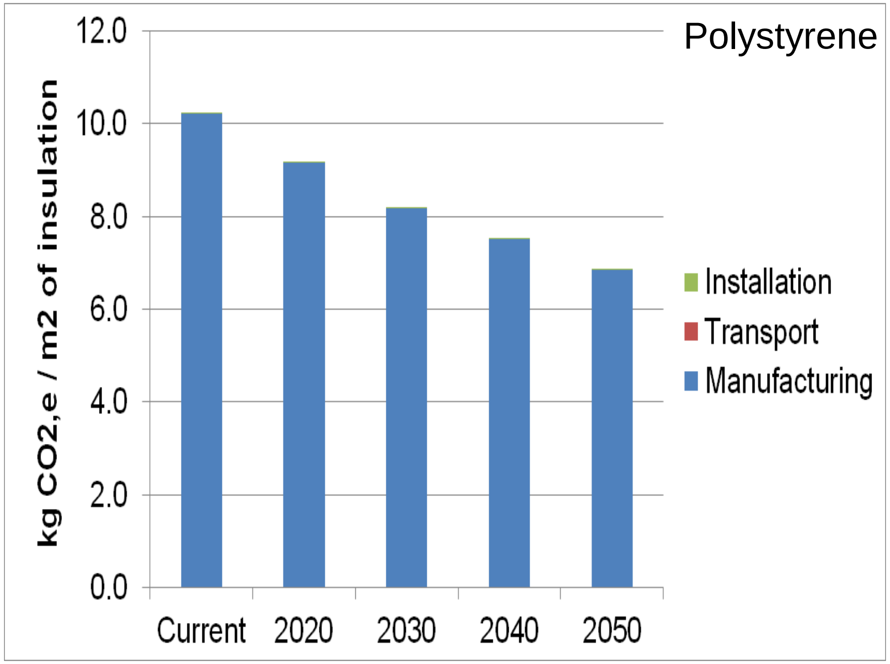
For both insulation materials, almost all LCEs arise from the manufacturing stage. The reduction in LCEs is attributed to reduction over time in material carbon and grid intensities (based on the IEA 2DS). By 2050, LCEs decrease by 16% for rockwool and by 32% for polystyrene.





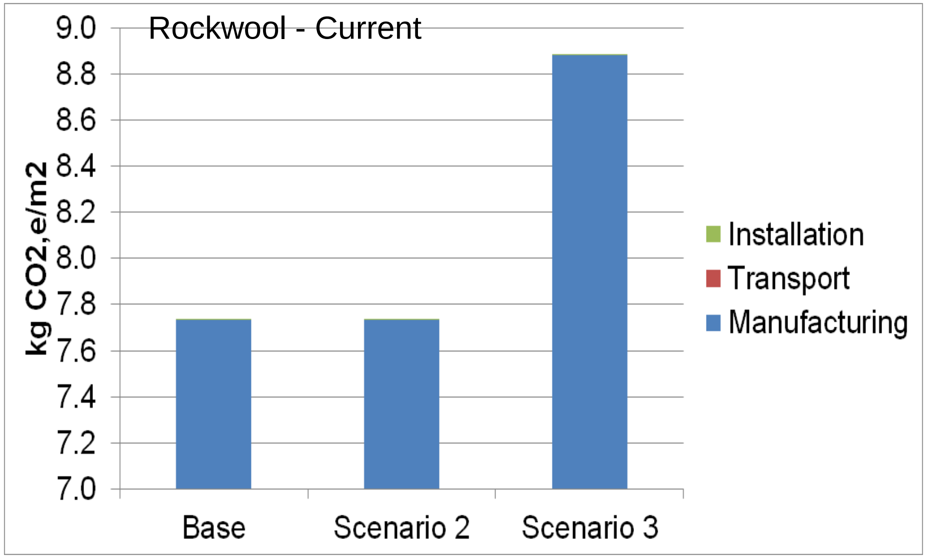
Sensitivity analysis and Results

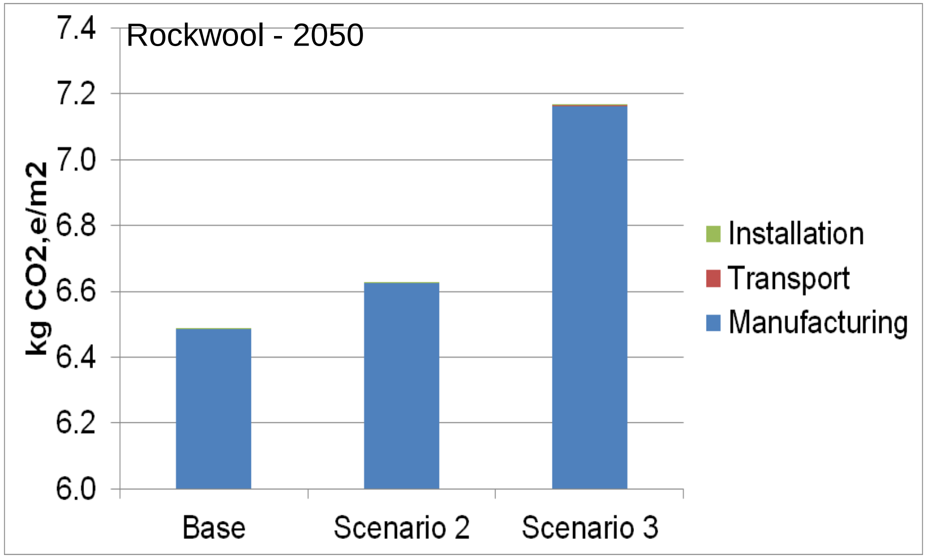
The following table describes the various scenarios tested.

Parameter		Carbon / grid intensity scenario	Manufacture location
Base-Scenario 1		IEA 2DS	UK
Scenario 2	Alternate material carbon intensity and grid intensity	IEA 4DS	UK
Scenario 3	Manufacturing in non-OECD Europe	IEA 2DS	non-OECD Europe

Sensitivity results for Rockwool

Manufacturing remains the key life cycle stage contributing to overall LCEs. The alternate carbon intensity / grid intensity scenario (based on the IEA 4 DS), does not affect current LCEs but will slightly increase LCEs in 2050. Considering a scenario where manufacturing is in non-OECD countries, LCEs could increase by 10-15%. The increase is attributed to higher carbon and grid intensities in non-OECD countries in comparison to the UK in 2050.

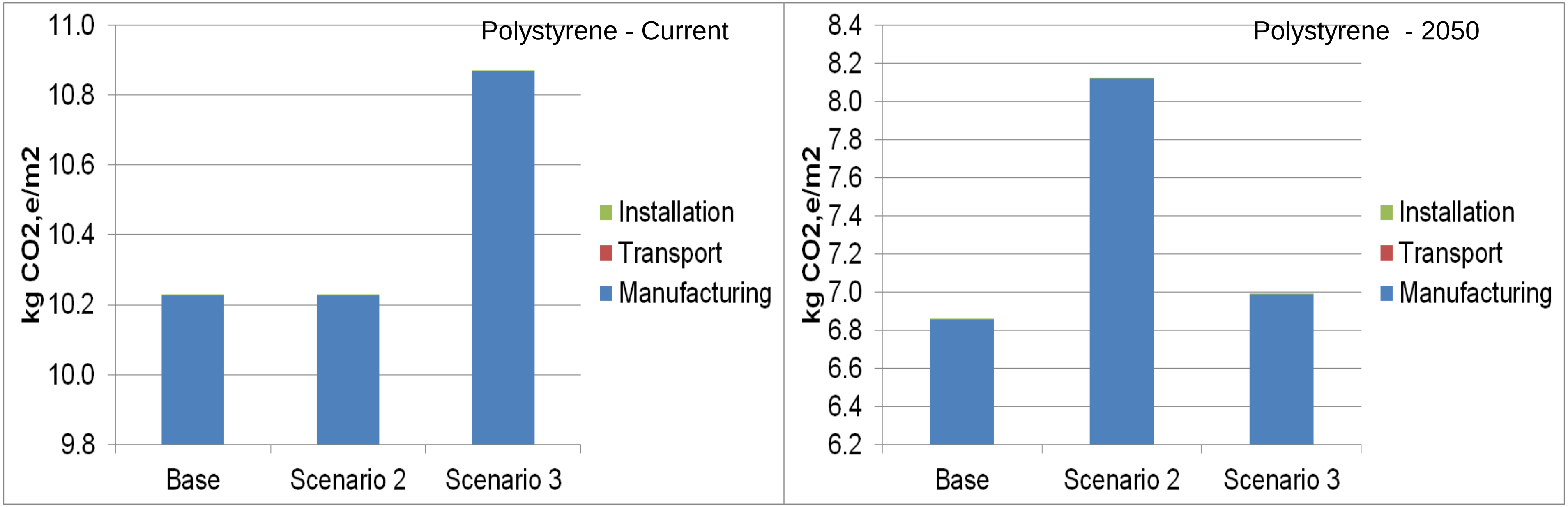




Sensitivity results for Polystyrene

Manufacturing remains the key life cycle stage contributing to overall LCEs with LCEs from installation and transport being negligible. The alternate carbon intensity / grid intensity scenario (based on the IEA 4 DS), does not affect current LCEs but will increase LCEs in 2050 by more than 15%. In comparison to rockwool, the materials used in the manufacturing of polystyrene are more carbon-intensive and so a more pronounced effect is observed when 4DS replaces 2DS.

Considering a scenario where manufacturing is in non-OECD countries, current LCEs could increase by about 7%.



Scenario description as shown on slide 129

Conclusions

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- Life cycle emissions for rockwool are estimated to be 7.7 – 8.9 kg CO_2/m^2 and for polystyrene foam as 10.2 – 10.9 kg CO_2/m^2.

- The analysis presented here based on the functional unit as defined by BRE using a resistance of 3 m^2.K/W and based on an insulation panel area of 1 m^2.

- The literature available on LCEs from insulation material is limited. Variation in the results reported by the literature is attributed to assumptions about the functional unit used where in most cases a resistance of 1 m^2.K/W is assumed.

- For both Rockwool and polystyrene, manufacturing is the life cycle stage that contributes more than 99%. Emissions associated with the installation (including transport of materials as well as personnel) are found to be negligible.

- The material carbon intensities and grid intensity are the key factors which could influence LCEs now and in the future. Replacing the 2DS scenario with the alternate 4DS in 2050, could increase LCEs by 2% for rockwool and by more than 15% for polystyrene, the manufacture of which is more carbon-intensive. Non-OECD manufacturing will lead to higher LCEs now and in the future for both rockwool and polystyrene. The effect of this scenario in 2050 is more pronounced for rockwool due to the higher UK / non-OECD difference fro materials used in the manufacture of rockwool in comparison to polystyrene.

- The base scenario assumes UK manufacturing. Assuming non-OECD manufacturing could increase current LCEs by 16% for Rockwool (10% in 2050) and by 7% for polystyrene.

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The Transport Sector

Road transport technologies

Introduction to the transport technology analysis

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- **Selection of transport technologies**
  - Available time and resources necessitated a focus on limited selection of technologies. This selection was based on their anticipated long-term potential for GHG emission reductions.
  - LCEs for selected base cases for cars (petrol ICE) and trucks (diesel ICE) are likely to be easily transferable to similar ICE options (i.e. diesel cars, gas-fuelled trucks) using simple assumptions/adjustments outside of the project if necessary.
- **Sensitivity model was developed and used to:**
  - Estimate current LCEs in the UK based on UK-specific data
  - Project current emissions into the future based on the base scenario
  - Test the effect of specific key parameters on LCEs in the future
  - Provide and understanding of the breakdown of LCEs and their geographical locations
- **Important caveats for the analysis**
  - The potential future impacts of biofuels were excluded from the analysis (set at 2012 pump mix)
  - The main purpose/objective of the work was to understand/identify (a) key influencing parameters in future LCEs, (b) potential impacts of future technologies on the geographical distribution of emissions. It was not to rate technologies against each other.
  - Technology comparisons were used mainly to identify areas for particular focus

The road vehicle lifecycle

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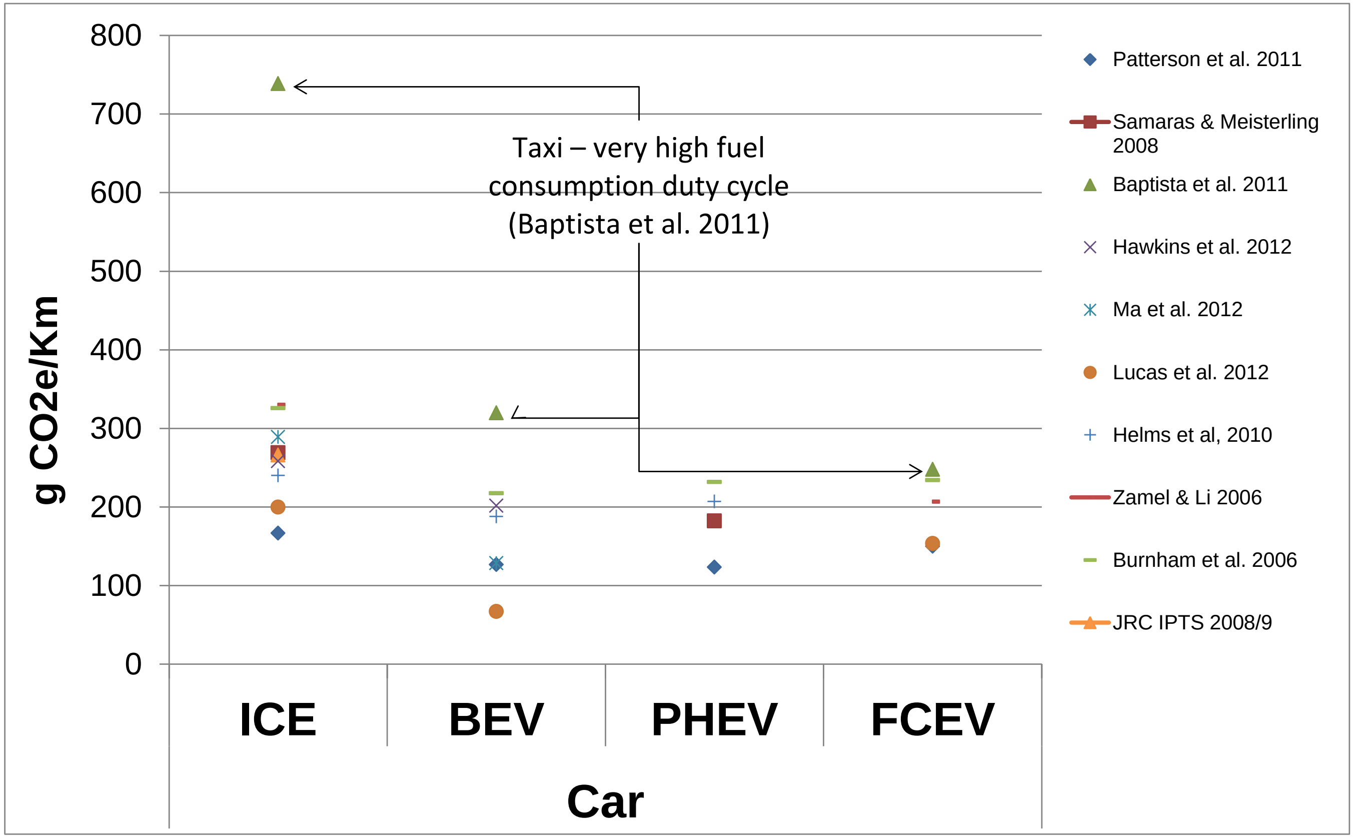
- **Vehicle Manufacture**
  - Materials (Fe, Al, etc)
  - Components
  - Manufacturing energy
- **Vehicle Transport**
  - Road
  - Rail
  - Ship
- **Vehicle Operation**
  - Energy Consumption
  - Maintenance
  - Refrigerant leakage
- **Refuelling Infrastructure**
  - Conventional fuels
  - Electric recharging
  - Hydrogen refuelling
- **End of Life Disposal**
  - Recycling
  - Refrigerant
  - Fuel use

Five key stages were identified as accounting for the most significant GHG emission components of the road vehicle lifecycle (that could also reasonably be quantified)

Range of overall LCEs in the literature

Road transport technologies



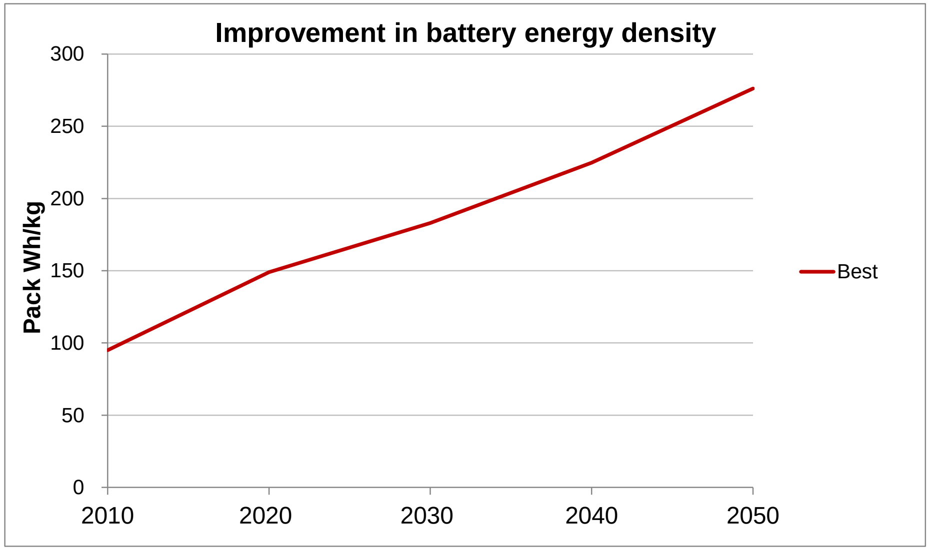
- A wide range of studies were identified and preliminarily screened for suitability
- The 12 studies that were selected to be taken forward for further analysis included some or all of the following elements:
  - ✓ They compared as many technologies as possible
  - ✓ They provided sufficient detail/ breakdown for the analysis
  - ✓ They provided additional information /detail on particular aspects (e.g. battery technology, refuelling infrastructure, etc.)
- Other studies were also used to provide/supplement key data

- The principal differences for cars in the studies were due to a combination of the following principal factors: (i) lifetime km, (ii) vehicle size, (iii) lifecycle stages covered, (iv) grid intensity, (v) batteries (size, GHG intensity).
- Only two sources were identified for diesel ICE trucks (Gaines 1998 and AEA Technology plc 2012), which provided similar results. No LCE studies were identified for FCEV trucks. Therefore information was collected for FCEV cars to be used as a proxy/for adaptation to develop estimates for articulated HGV FCEVs in the calculation framework.
- A study that also included diesel taxis (Baptista et al. 2011) was included to facilitate this analysis of FCEVs.

Transport base data

Approach and key assumptions (see Annex for more details)

- CCC provided default values for key parameters for the different technologies:
  - Kerb weight, lifetime, annual km, % miles electric, vehicle efficiency (in MJ/km for both electric and non-electric operation), fuel cell/hydrogen storage tank/battery sizes (/capacity)
- The kerb weight figures for cars were revised by Ricardo-AEA to factor in the additional weight of batteries and other systems (e.g. fuel cells, H_2 storage) where relevant:
  - The revised estimates for vehicle weight were cross-checked relative to the weights of PHEVs and BEVs versus ICE from Patterson et al. (2011)
  - Original 1407 kg for all cars → higher mass for PHEV / BEV, declining in future periods based on increases in battery energy density (from batteries study for CCC, 2012) and battery size
- Vehicle kerb weights were also adjusted for the weight reduction inherent in the future efficiency figures (in MJ/km) = 20% for cars and 10% for HGVs by 2050
- Detailed tech comparisons were made based on consistent sources, exploring variations and the reasons for these:
  a) Using source assumptions for annual km, vehicle size (weight) and efficiency
  b) Normalising these parameters to CCC default values (also for % electric km)
- Operational average electricity EFs including upstream emissions were also developed



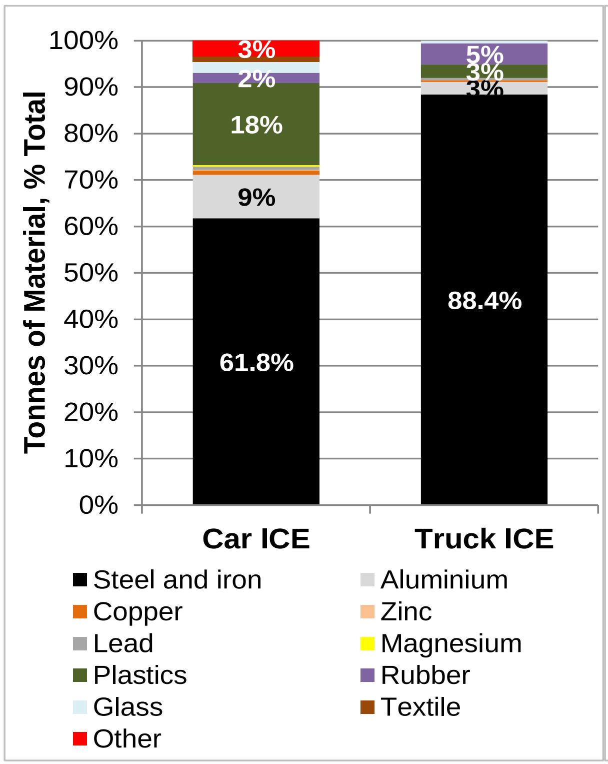
Comparison of key assumptions from the literature

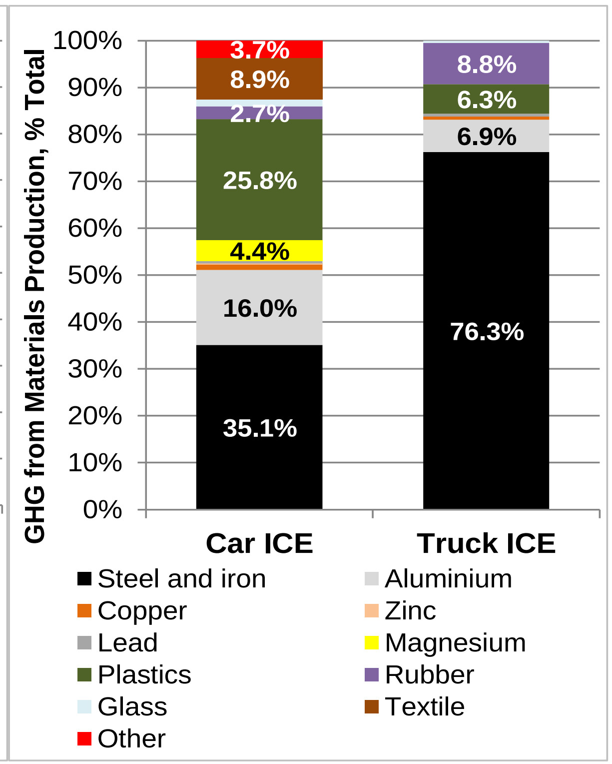
Passenger Car Technologies

		CCC Study for 2010	Patterson et al. 2011	Baptista et al. 2011	Hawkins et al. 2012	Lucas et al. 2012	JRC IPTS 2008/9	Helms 2010	Samaras & Meisterling 2008
General	Petrol or Diesel gCO2/kWh	301 / 320	288	325	320	313	290	341	378
	Electricity gCO2/kWh	372	500	540	561	244	N/A	676	670
	Hydrogen gCO2/kWh	463	359	319 / 433	N/A	684	N/A	N/A	N/A
	Lifetime mileage (km)	182,000	150,000	563,250	150,000	150,000	211,250	150,000	240,000
	Battery intensity, kgCO2/kWh	161	161*	48	258	49	N/A	125	120
	Biofuel included?	No	Yes	No	No	No	Yes	No	No
	Region for analysis	UK	UK	UK	Europe	Portugal	Europe	Germany	USA
	Breakdown of production GHG?	Mix	Compon'ts	Materials	Both	Neither	Materials	Neither	Neither
Petrol ICE Car	Kerb weight (kg)	1,407	1,340	1,895	1,295	1,521	1,240		
	Vehicle MJ/km (real world, non-elec)	2.77	1.58	8.00	2.25	1.98	3.02		
BEV Car	Kerb weight (kg)	1,561	1,480	2,834	1,521	1,235			
	Vehicle MJ/km (real world, electric)	0.69	0.47	1.80	0.48	0.83			
	Battery pack size (kWh)	44.1	45.0	63.0	24.0	53.0			
	Battery pack weight, kg	464		1060	214	408			
Petrol PHEV Car	Kerb weight (kg)	1,532	1,460					1,500	1,148
	% miles electric	31%	40%					49%	47%
	Vehicle MJ/km (real world, electric)	0.69	0.37					0.76	0.72
	Vehicle MJ/km (real world, non-elec)	2.12	1.14					1.99	1.64
	Battery pack size (kWh)	8.3	4.8					12.5	6.7
	Battery pack weight, kg	121	37						75
FCEV Car	Kerb weight (kg)	1,481	1,410	2,060		1,600			
	Lifetime mileage (km)	182,000	150,000	563,250		150,000			
	Vehicle MJ/km (real world, non-elec)	1.32	1.00	2.52		0.65			
	Fuel cell size (kW)		73	70		100			
	Fuel tank capacity (kWh)					134			
	Battery pack size (kWh)	2.5	1.8	20.0		2.3			

Literature assumptions on vehicle manufacturing

- The reviewed studies do not provide consistent breakdowns, and are typically split by:
  a) Material use + process energy use (fuel often not specified, but mostly electricity), or
  b) Vehicle component (e.g. glider, engine, transmission, **battery**, etc.), or
  c) A combination of the two
- Indications on the relative significance of different materials in terms of their weight and GHG emissions was available for both cars and trucks from AEA Technology plc (2012)





- For more consistent comparisons of the LCE breakdowns from the literature, the 'Raw values' from studies reviewed in more detail were normalised to an extent by recalculating production emissions using consistent assumptions for material GHG intensity (in $kgCO_2e/kg$ material) where the vehicle weight and % composition by material was available

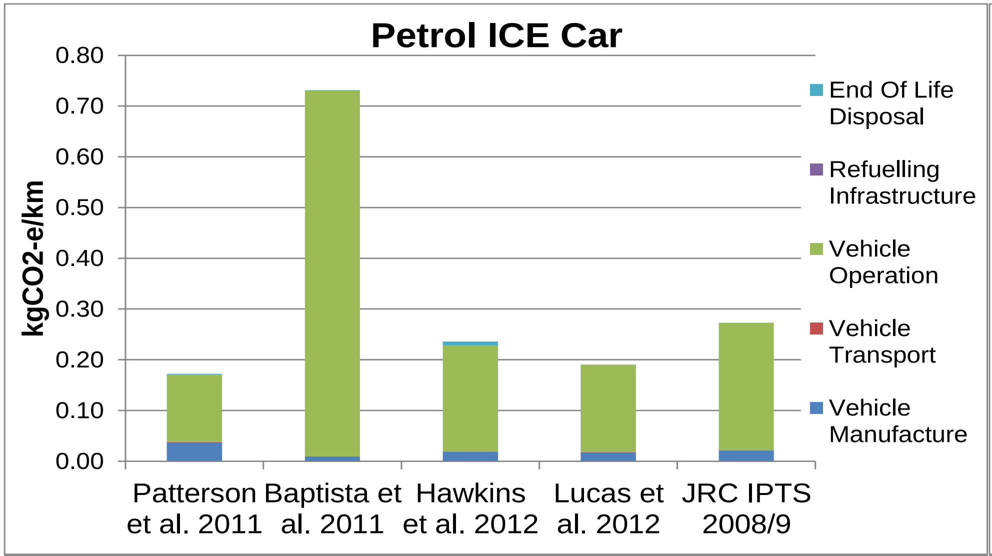
Notes: 'Other' includes composites (CFRP, GFRP), Lubricant oil, refrigerants, and other materials

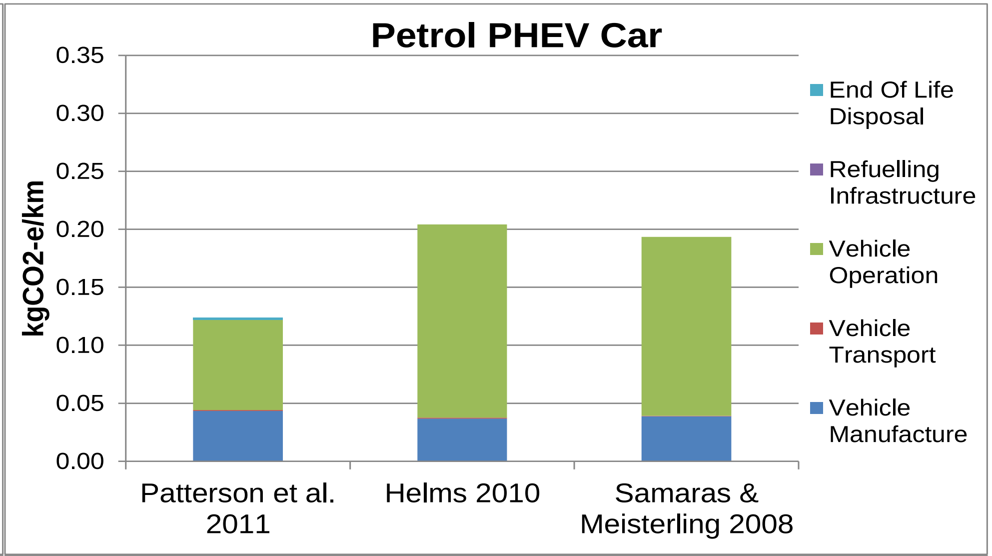
* With consistent material GHG emission factors applied

Breakdown of current LCEs based on the literature

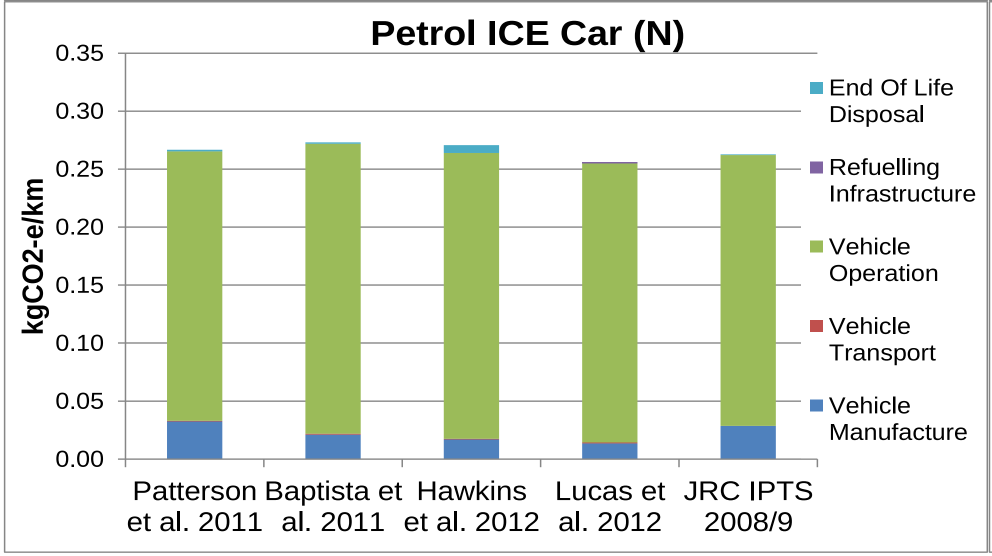
Petrol ICE and PHEV Car

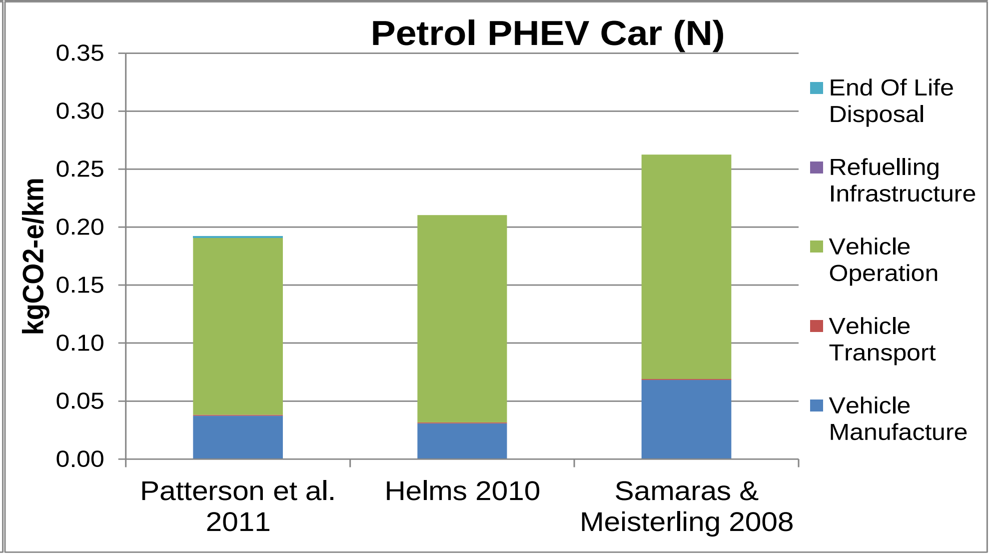
"Raw" values*





Normalised





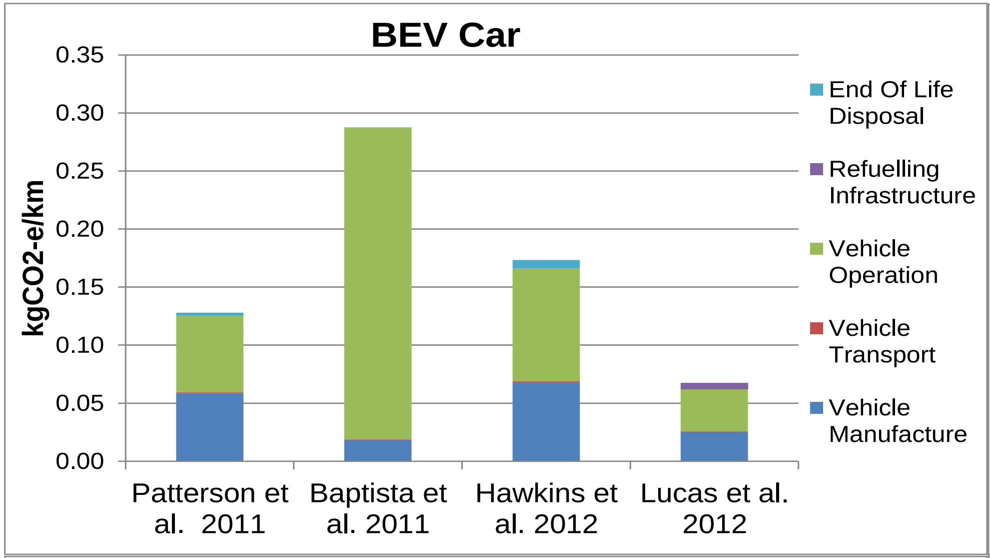
- Additional normalising was carried out to scale for study default size (kg), lifetime km, MJ/km and % electric km
- Remaining differences due principally to assumptions made for battery production and electricity emission factors

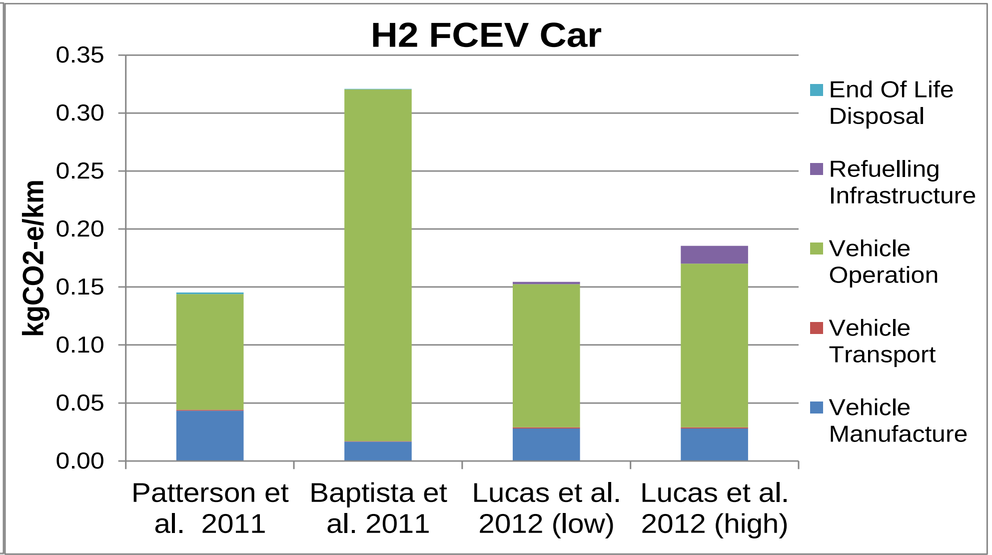
* With consistent material GHG emission factors applied

Breakdown of current LCEs based on the literature

BEV and H2 FCEV Car

"Raw" values*





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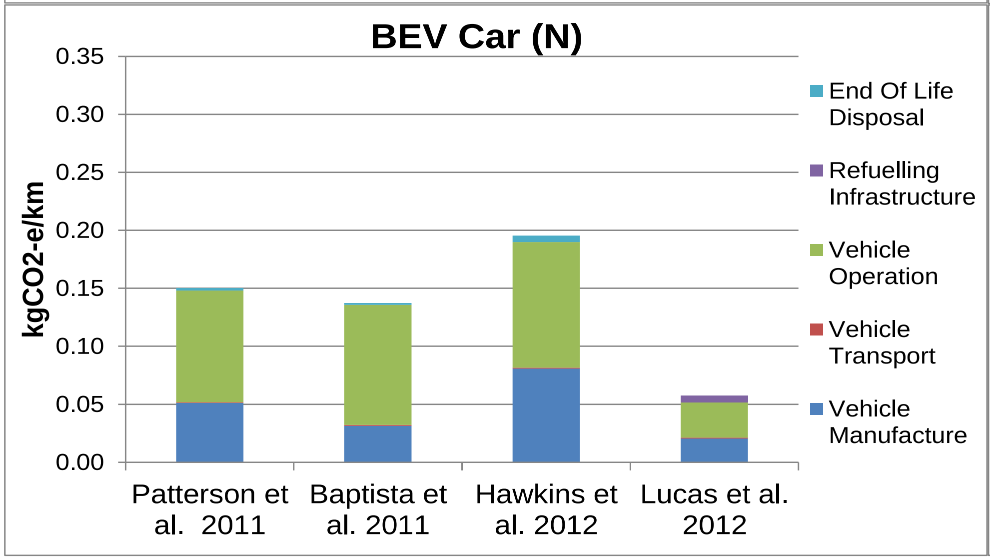
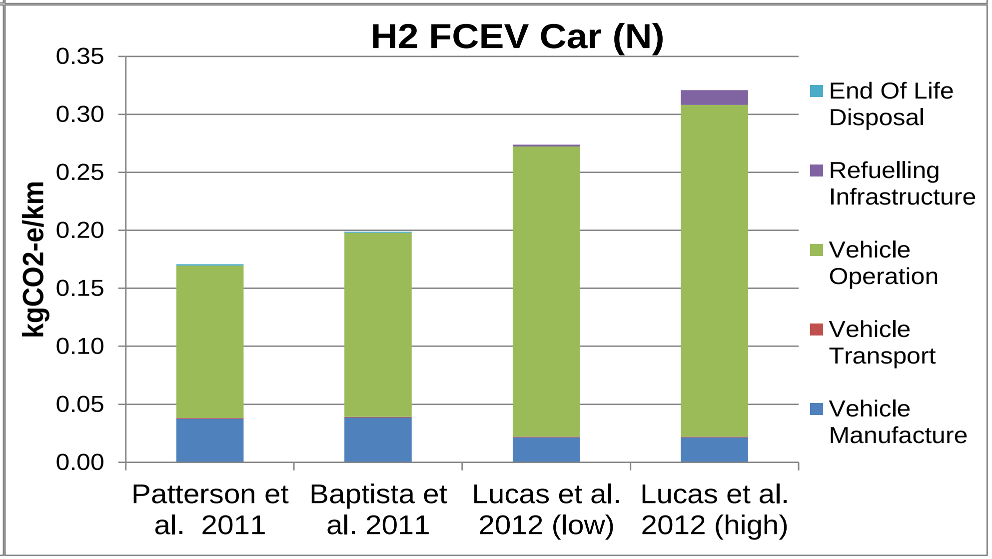




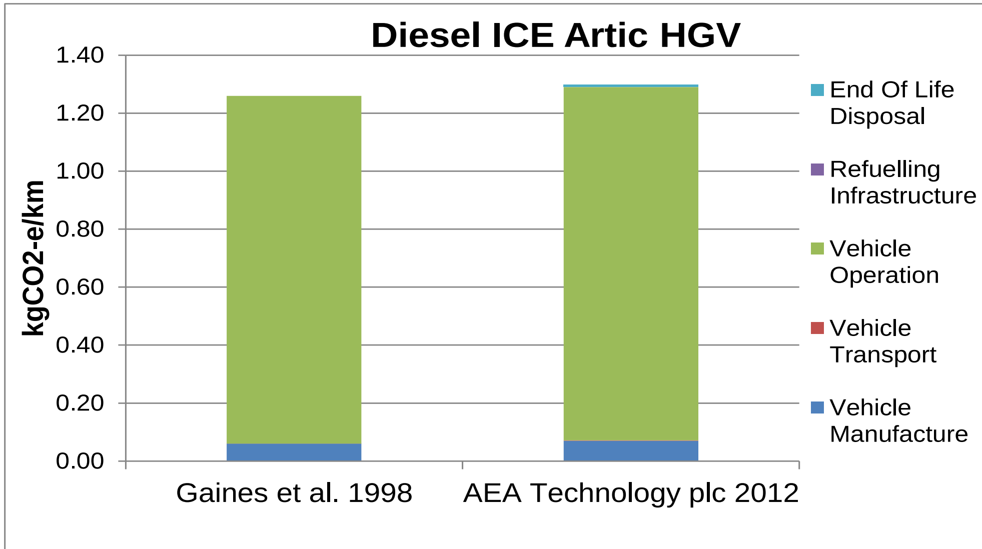
- As for PHEVs, the principal difference between studies post-normalisation is due to assumptions on battery intensity and operational electricity / hydrogen intensity

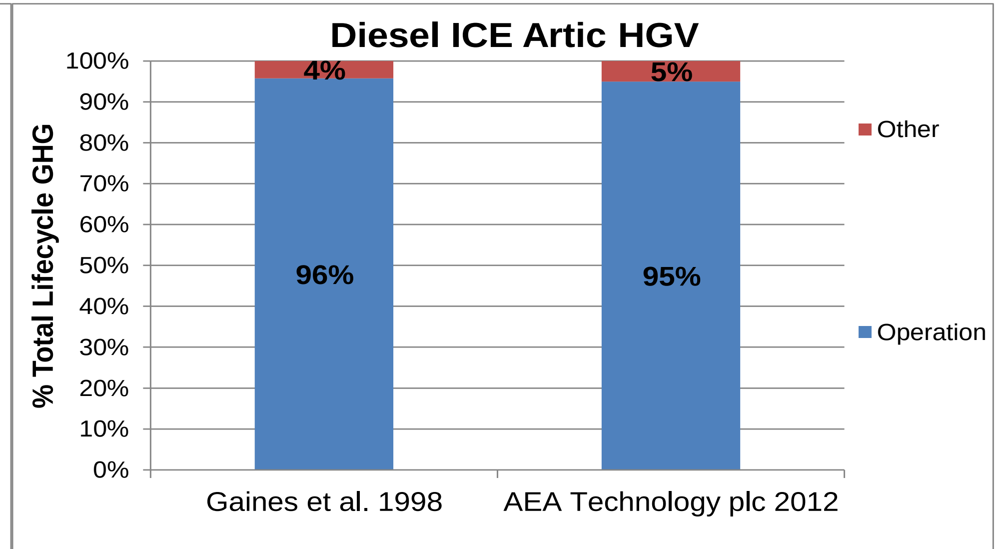
* With consistent material GHG emission factors applied

Breakdown of current LCEs based on the literature

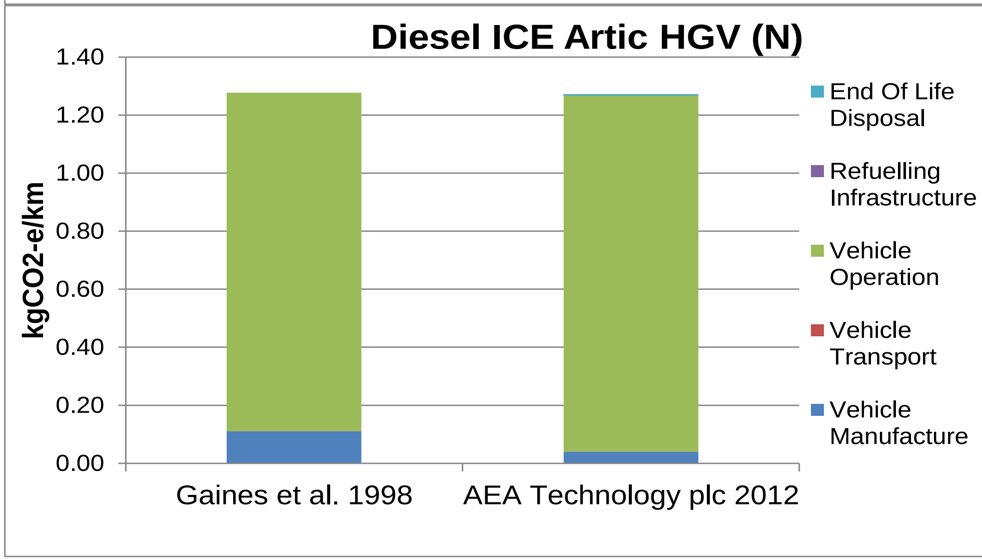
Diesel ICE Artic HGV

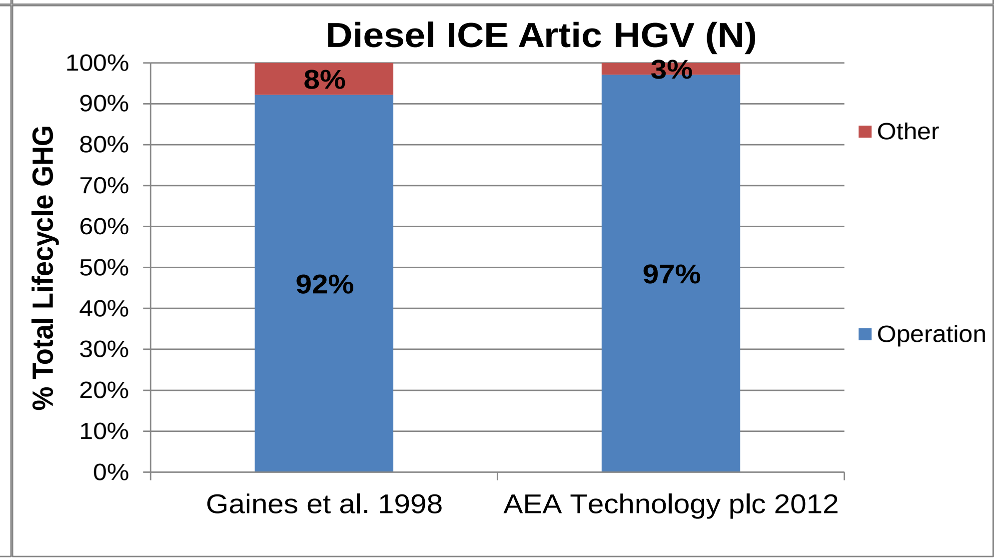
“Raw” values*





Normalised





- As for car technologies, the ‘Raw values’ already adjusted to study default assumptions on materials’ CO_2e/kg
- The vast majority of emissions from articulated HGVs arise from operational fuel use due to very high lifetime km

Key influencing parameters on road vehicle LCEs:
Factors used to inform scenario development

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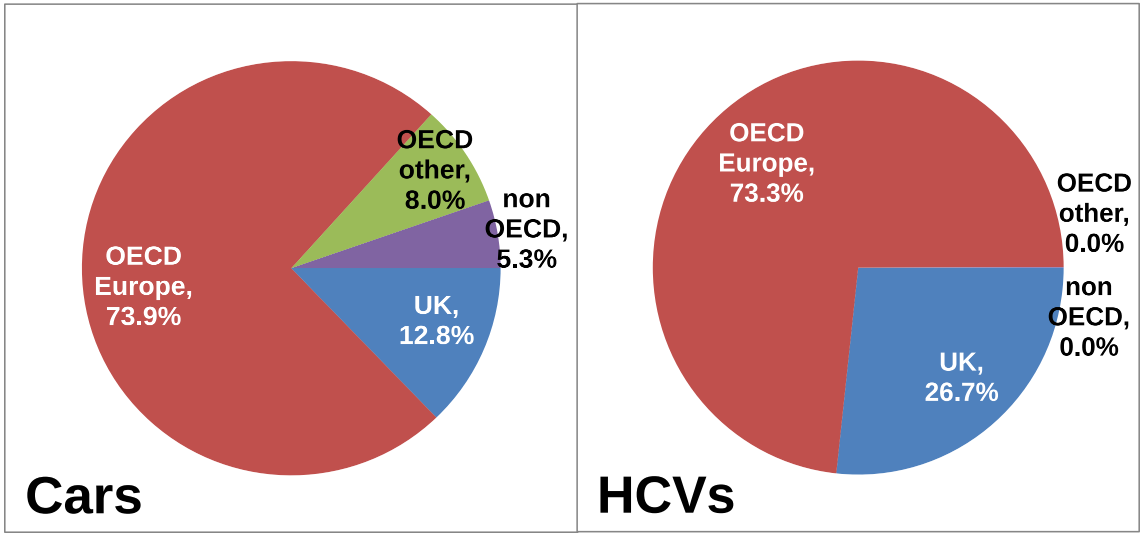
- There are a range of geographical and other factors that influence vehicle LCE
- Geographical factors:
  - Has a strong influence on the GHG intensity of materials, components and production electricity.
  - Advanced technology production could be more localised in the future (e.g. Nissan Leaf in UK)
  - SMMT (2012) UK sales data →



- Other key factors include:
  - The GHG intensity of electricity use for plug-in EV charging and hydrogen production pathways
  - Future vehicle weight /size reduction – has impact on the use of key materials (Al, CFRP)
  - **Batteries:** # of replacement batteries [and also improvement in battery energy density, future recycling GHG savings]
  - Refrigerant use in air conditioning – HFCs are to be phased out under EU legislation by 2020*
  - [The required density/type of electric or hydrogen distribution/refuelling infrastructure – there was insufficient information readily available to explore sensitivities within this project]

* Most likely replacement is expected to be CO_2 (GWP = 1) or HFO-1234yf (GWP = 4) (according to: http://www.allpar.com/eek/ac.html)

A further breakdown was modelled by applying consistent factors to lifecycle inventory datasets (see later slides for more info)

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Petrol ICE car manufacture			JRC IPTS 2008/9			Scenario LCA Data	
Materials	Iron	kg	118.1	X	kgCO$_2$e/kg	0.95	etc
	Steel		627.8			1.24	
	Aluminium		111.0			7.28	
	Copper		11.6			2.85	
	Zinc		2.5			2.14	
	Lead		8.8			1.76	
	Magnesium		2.7			48.5	
	Plastics		214.4			4.18	
	Rubber		26.7			2.85	
	Glass		29.7			1.42	
	Textile		12.9			20.3	
	CFRP		0.0			22.0	
	GFRP		0.0			8.00	
	Lubricating oil		7.7			1.00	
	Refrigerant		0.5 (R134a)			1.00	
	Other		65.6			4.18	
Energy	Electricity	MJ	5096		kgCO$_2$e/MJ	0.130	
	Natural gas		7065			0.063	
Other	Refrigerant leakage	%	3%		kgCO$_2$e/kg	1430	

Breakdown of LCEs from the developed model:

Detailed split for 2010 Petrol ICE and BEV cars

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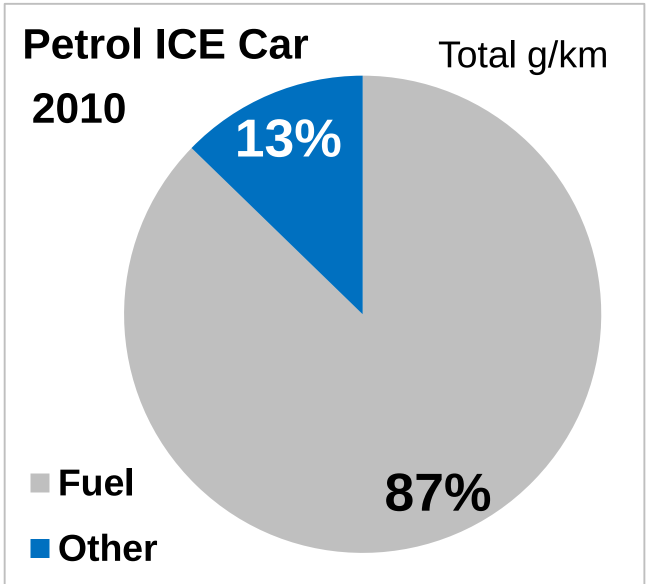

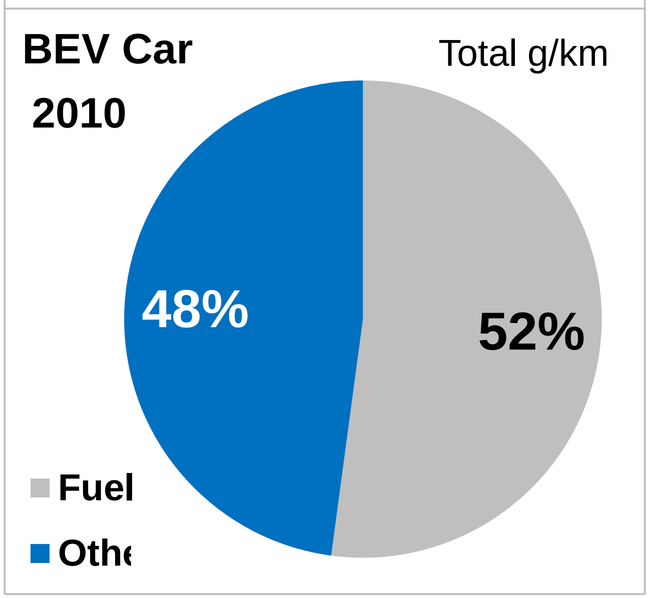

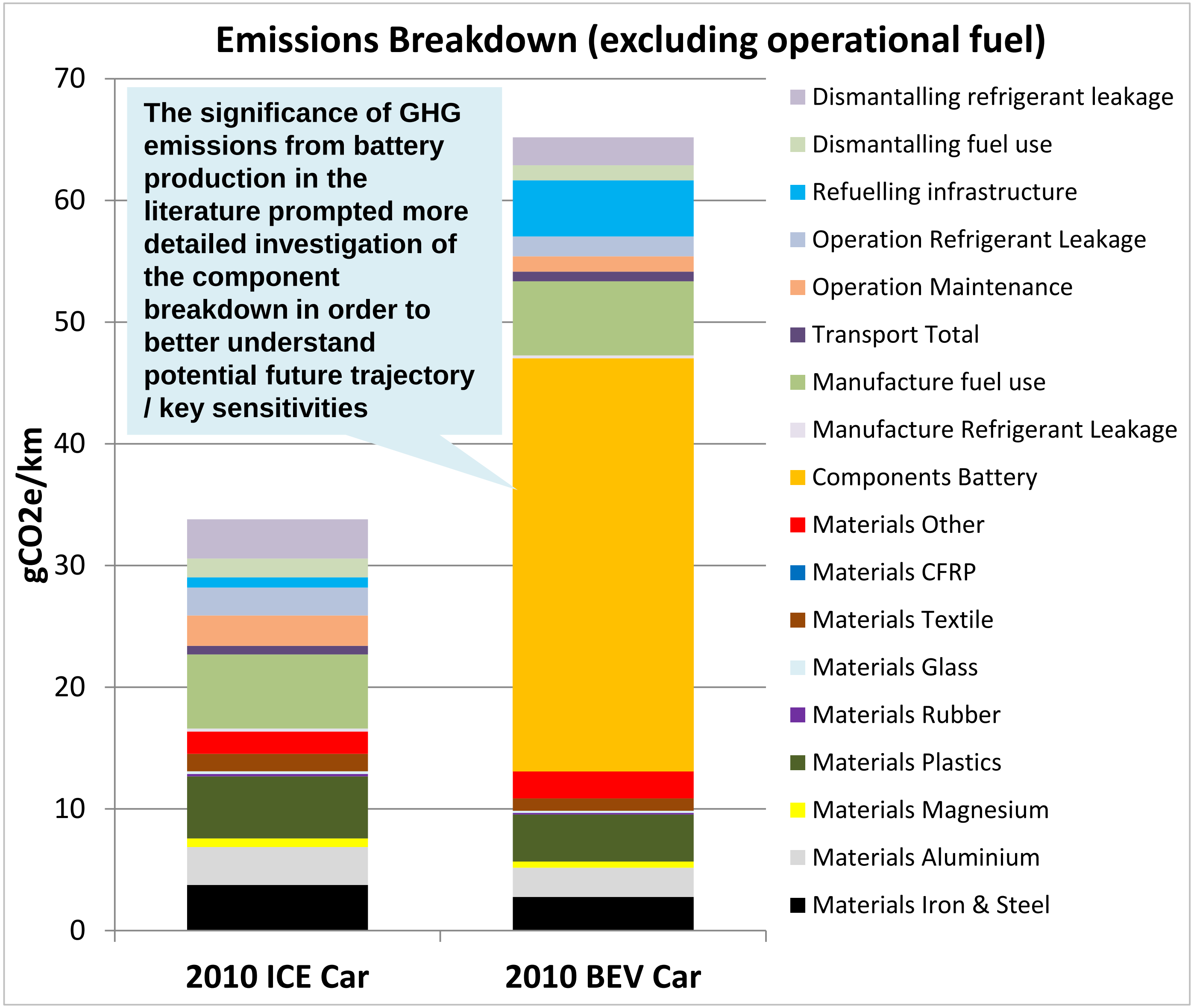

Breakdown of the road vehicle battery lifecycle:
Manufacturing energy is a significant component

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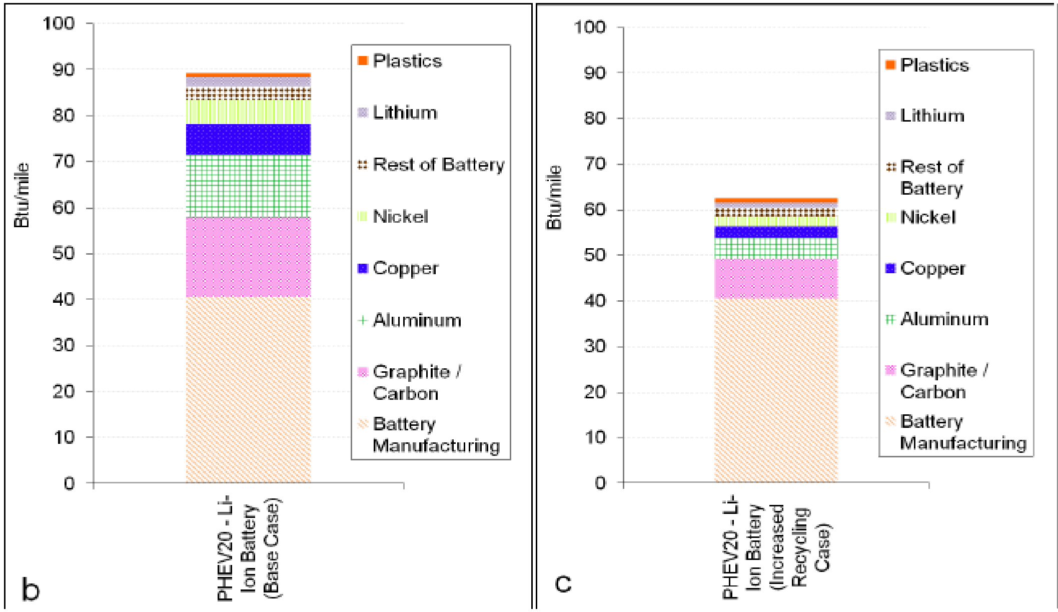

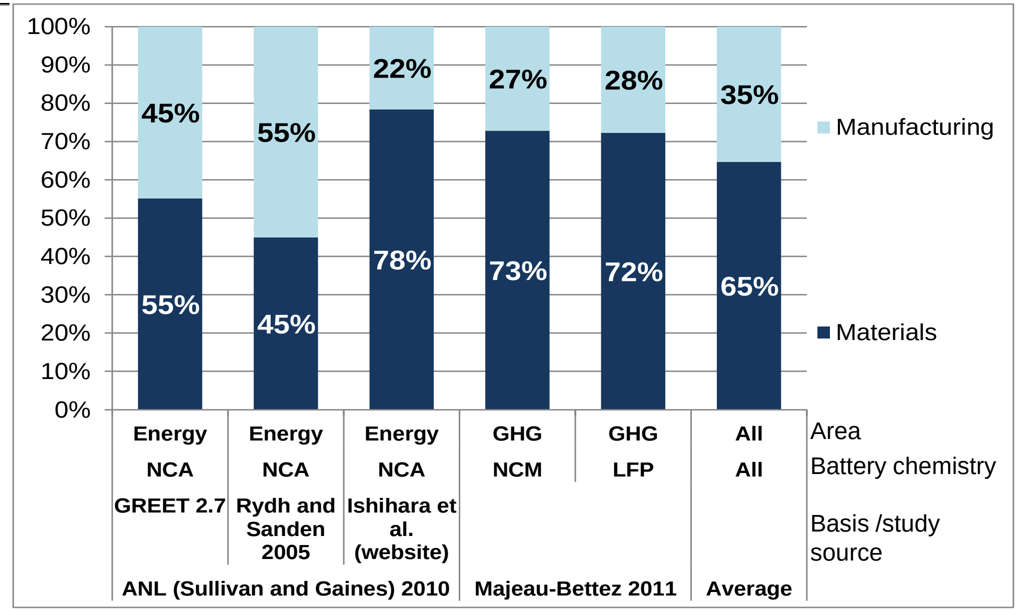

Source: Gaines et al (2011), based on GREET 2.7

- The review of literature shows ~22-55% energy/GHG is due to manufacturing
- There is a significant potential for savings through reducing GHG intensity of energy used in battery manufacture would therefore seem possible in the future.
- Also further reductions are possible from improved (closed-loop) recycling (versus current practices), and reduced material use (e.g. improved $kWh/kg_{battery}$).
- It is anticipated that in the future (i.e. once high EV volumes are reached) battery manufacture will be more localised i.e. near to regional production centres - as is currently generally the case with the rest of the component supply chain

Breakdown of LCEs from the developed model:

Future trajectory of detailed split for BEV cars (baseline)

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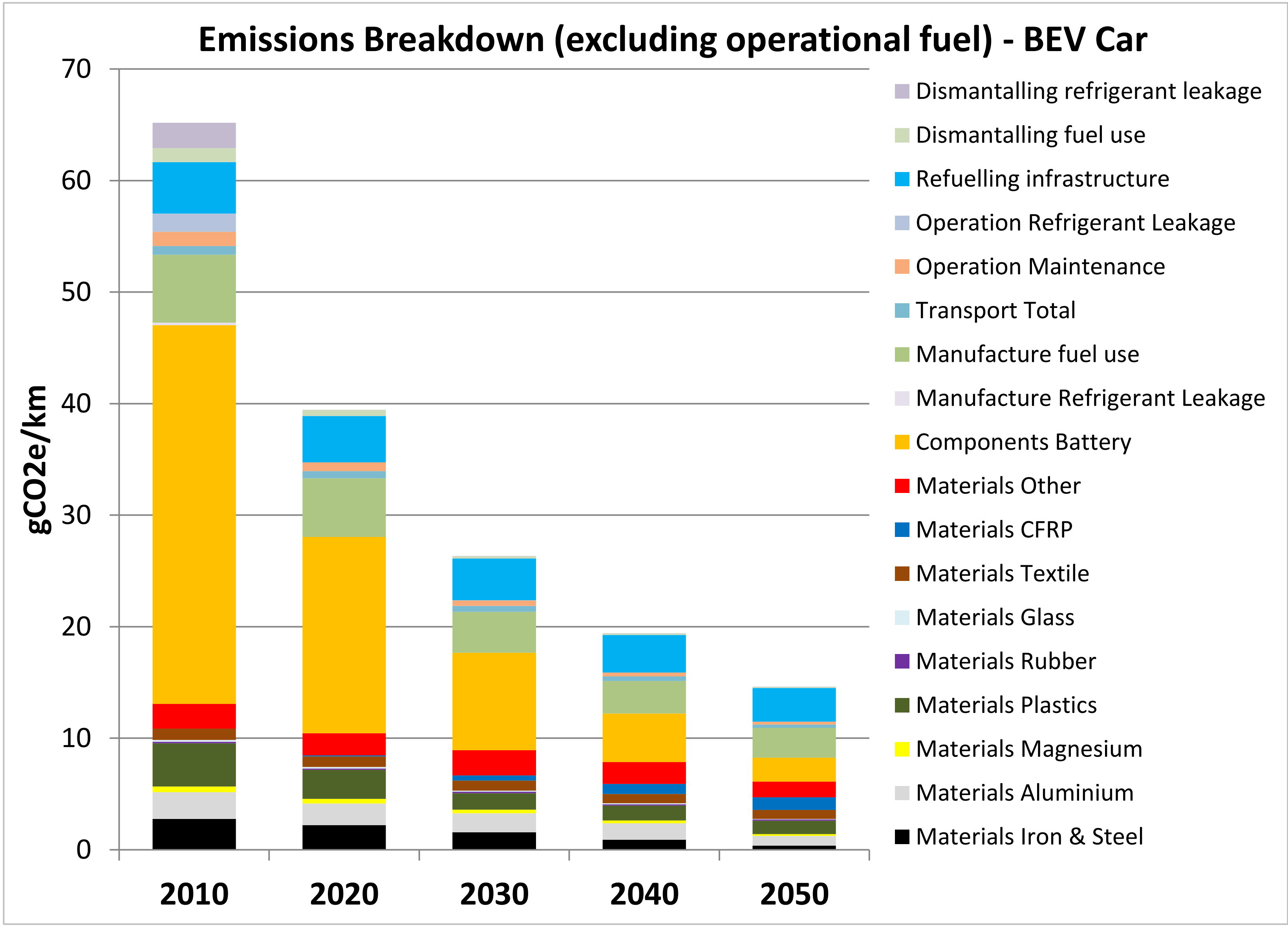
- The significance of batteries in the overall LCE footprint of BEVs is anticipated to decrease significantly in the long term under the base case:



Base case scenario assumptions:
Summary of main assumptions for base case, part 1

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- **Materials breakdown and manufacturing energy consumption:**
  - JRC IPTS 2008/9 – Based on European car averages, also includes estimates for impacts of lightweighting in shift of steel used to Aluminium and CFRP*
  - Transition in material breakdown 2010-2050 based on % lightweighting
  - For H2 FCEVs: Manufacturing emissions have been scaled up to account for lost load space/weight (so requiring more vehicles for same load) due to hydrogen storage requirements (3.5% in 2010, dropping to 1% by 2050 due to improved vehicle efficiency and storage density).
- **Location of production emissions:** based on weighted share of regions (different for cars, HGVs) calculated from SMMT (2012) data for 2011 new vehicle sales
- **Transport to market:** no studies identified provided this information, therefore assumptions had to be made for this study based on the sourcing of cars to the UK market, which were as follows:
  - UK sourced vehicle: av. of 200 km by truck
  - Europe sourced: assume average 400 km by truck, 750 km by both rail and ship
  - Other sourced (mostly S. Korea and Japan): 700 km by truck, 12,000 km by ship
- **Operational energy EFs:** based average over lifetime of vehicle operation (i.e. account for future energy decarbonisation assumptions)
- **Maintenance:** estimated based on JRC IPTS 2008/9 for ICE. Assume 80% of emissions for PHEV, 50% for BEV due to reduced maintenance / parts replacements (i.e. assume battery lasts the life of the vehicle)

* CFRP = carbon fibre reinforced plastic

Base case scenario assumptions:

Summary of main assumptions for base case, part 2

- **Refuelling infrastructure:** only a single study (Lucas et al. 2012) was identified with comparable data across different fuel types (i.e. liquid fuels, electricity and hydrogen)
  - Model assumptions based on Lucas et al. 2012, plus a 10% reduction in emissions per km every 10yrs as an approximation to account for both lower densities (vs # vehicles) and a reduction in the manufacturing and installation intensity of infrastructure.
  - PHEVs are assumed to share refuelling/charging infrastructure based on % electric km
- **Battery/fuel cell recycling savings:** currently 100% recycling, but with no GHG savings. 50% GHG savings in materials component is possible (based on Gaines et al 2011). Assume 0% of potential savings in 2010, 40% in 2020, 100% from 2030.
- **Refrigerant:** leakage and recovery rates taken from Annex 8 of DCF 2012. A switch from R134a to CO_2 or HFO-1234yf is assumed by 2020
- **End-of Life (EOL) materials:** utilise a recycled content methodology (so recycling credits counted up-front), in line with most studies. Additional assumptions based on refrigerant recycling (from DCF 2012)
- **EOL energy:** average of Patterson et al. 2011 and JRC IPTS 2008/9
- **Biofuels:** the potential impacts of biofuels are currently highly uncertain – their level of availability/use in different sectors, net GHG savings, etc. At the 2050 time-horizon it is anticipated that sustainable biofuels available to transport will be prioritised for use in aviation and shipping. **Potential future increases in the use biofuels are therefore excluded from the analysis*.**

* Emission factors for petrol and diesel include biofuels a their 2012 average levels for public refuelling stations

Base case scenario assumptions:
Refuelling infrastructure system boundaries for supply chains

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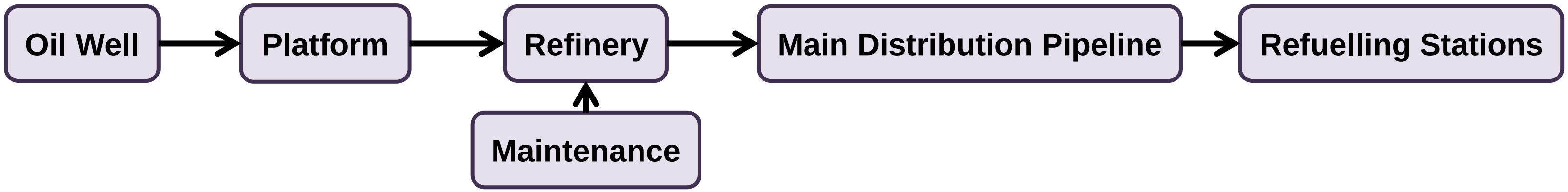
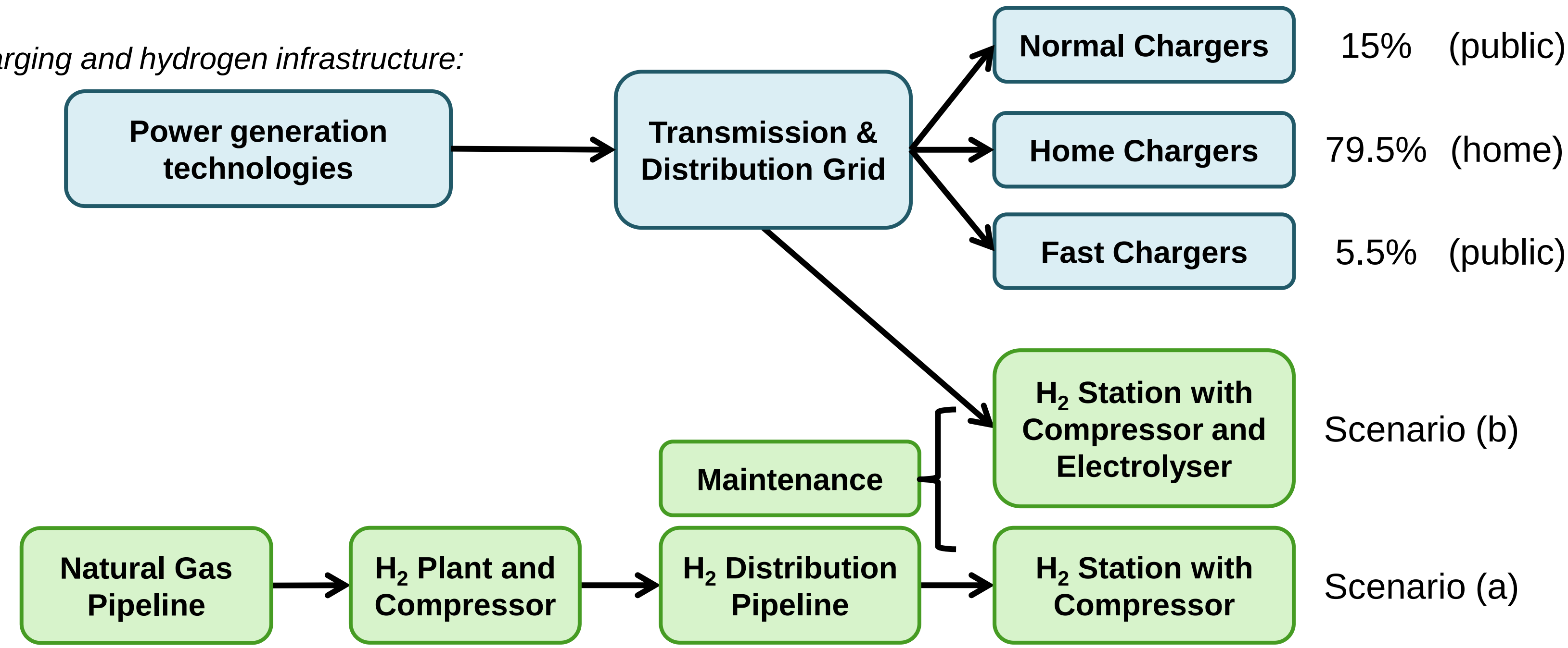
- Assumptions were based on Lucas et al. (2012), which included the following chains:
  - *Conventional liquid fuel infrastructure:*

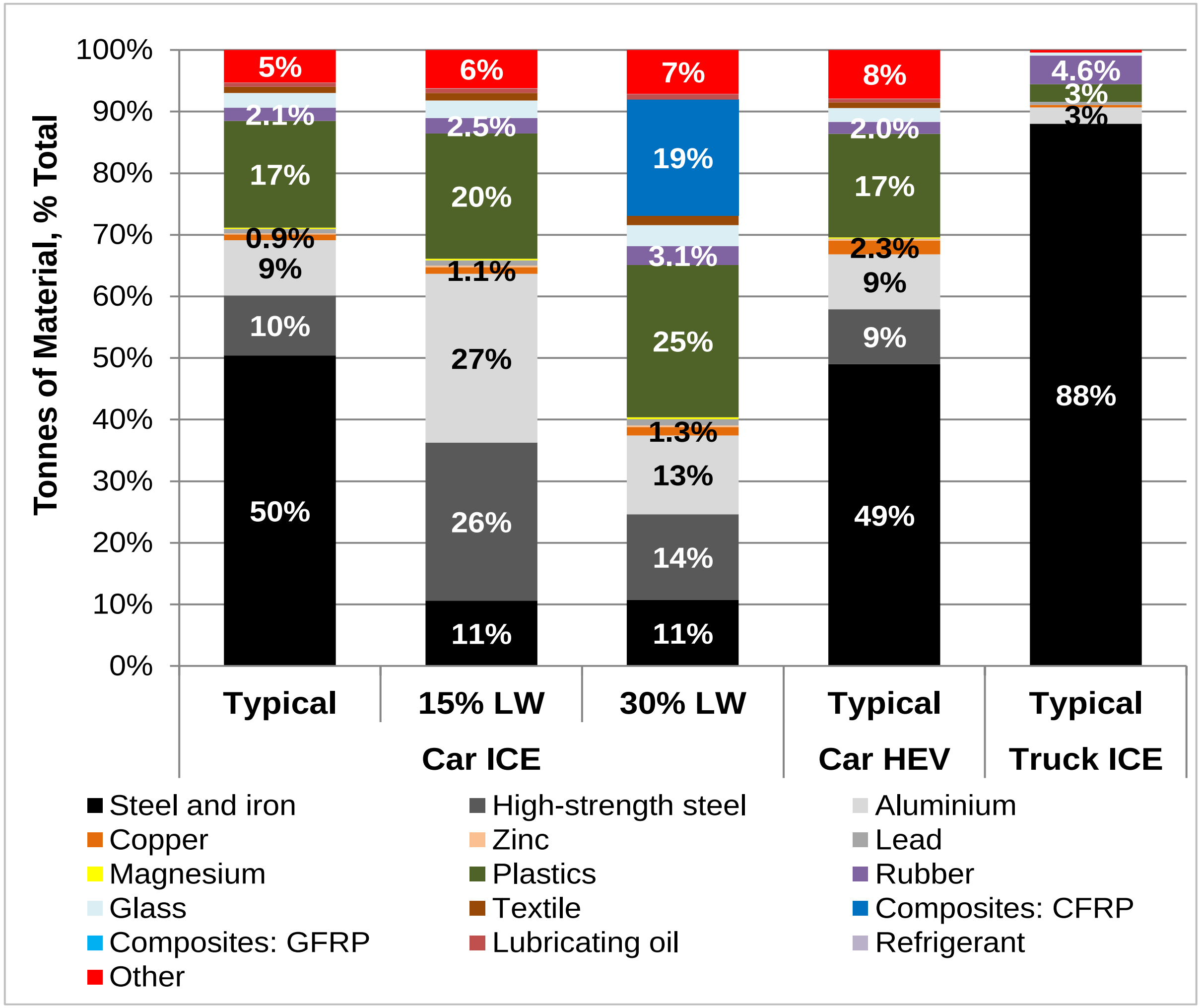


  - *Electric charging and hydrogen infrastructure:*



Base case scenario assumptions:
Vehicle materials breakdown – Source Data

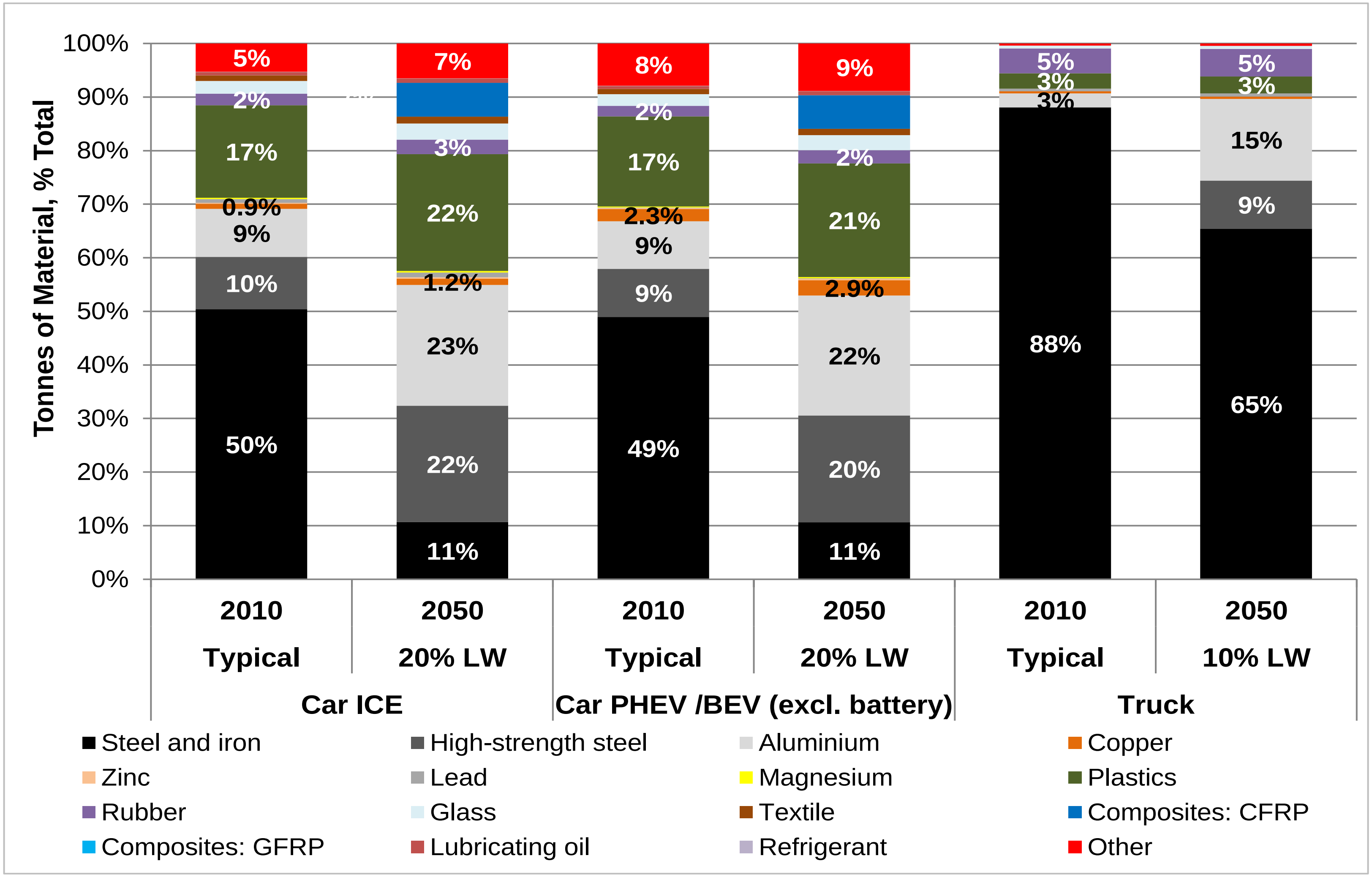
- Source data for **cars** was JRC IPTS 2008/9: Based on European car averages, also includes estimates for impacts of lightweighting in shift of steel used to Al, CFRP
- Data also includes estimates for revised material breakdown for hybrid electric vehicles
- Source data for **heavy trucks** (>32 tonnes) was from AEA Technology plc (2012)



Note: includes materials used in the batteries for both conventional and hybrid ICEs

- In final calculations the transition in material breakdown 2010-2050 was based on the % lightweighting inherent within MJ/km assumptions (20% for cars, 10% for HGVs by 2050

Base case scenario assumptions:
Vehicle materials breakdown – Final



- The transition in material breakdown from 2010-2050 is based on the % lightweighting by year
- Truck materials are dominated by structural elements, and therefore the powertrain type has little impact on the overall materials composition

Base case scenario assumptions:
Recycling rates and recycled content

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- Automotive recycling rates are much higher than typical recycled content of materials used in their manufacture (particularly for iron, steel and aluminium that form the biggest part of the materials footprint), in part due to the EC Directive on end of life (EOL) vehicles that requires minimum recovery and recycling rates to be achieved (and increasing in future years)
- The default assumption set for the base case was to calculate material GHG intensities (in $kgCO_2e/kg$ material) assuming the recycled content share is based upon automotive recycling rates.

Material	Recycling Rate		
	Global Av.	Auto Current	Auto Future
Aluminium	33.0%	63.0%	98.0%
Carbon FRP	0.0%	0.0%	0.0%
Copper	37.0%	41.0%	80.0%
Glass	N/A	10.0%	60.0%
Lead	61.0%	98.0%	100.0%
Magnesium	50.0%	63.0%	100.0%
Lubricating oil	N/A	98.0%	98.0%
Plastics	N/A	23.7%	93.4%
Rubber	N/A	82.0%	85.0%
Steel and iron	39.0%	93.5%	98.4%
Textile	N/A	45.0%	80.0%
Titanium	54.0%	54.0%	54.0%
Zinc	30.0%	38.0%	90.0%

Base case scenario assumptions:
Energy and Materials Intensity trajectories

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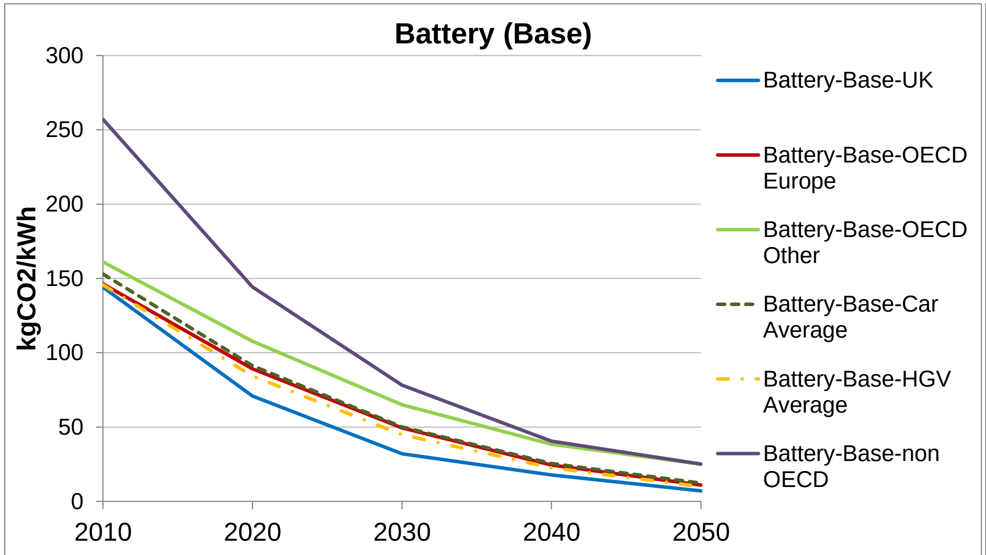
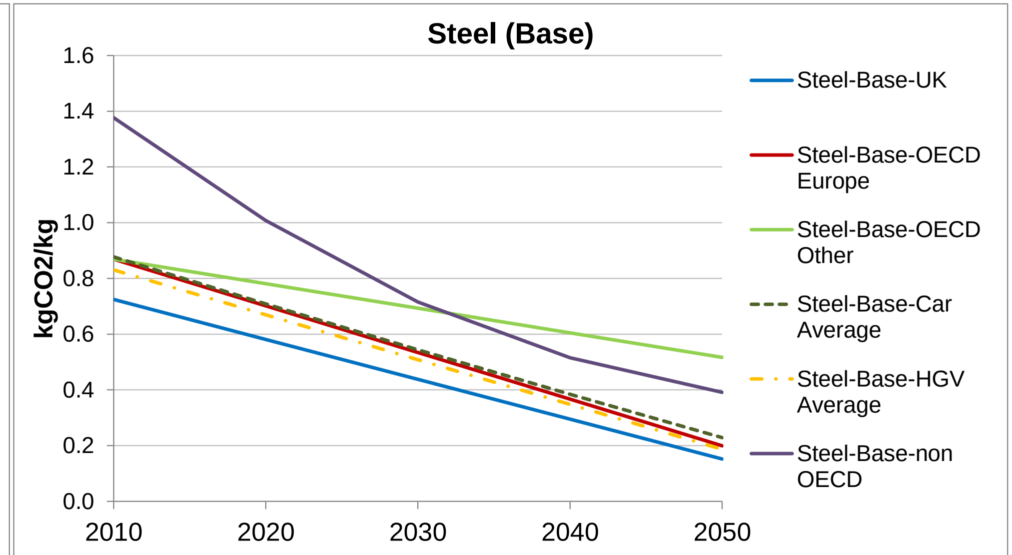
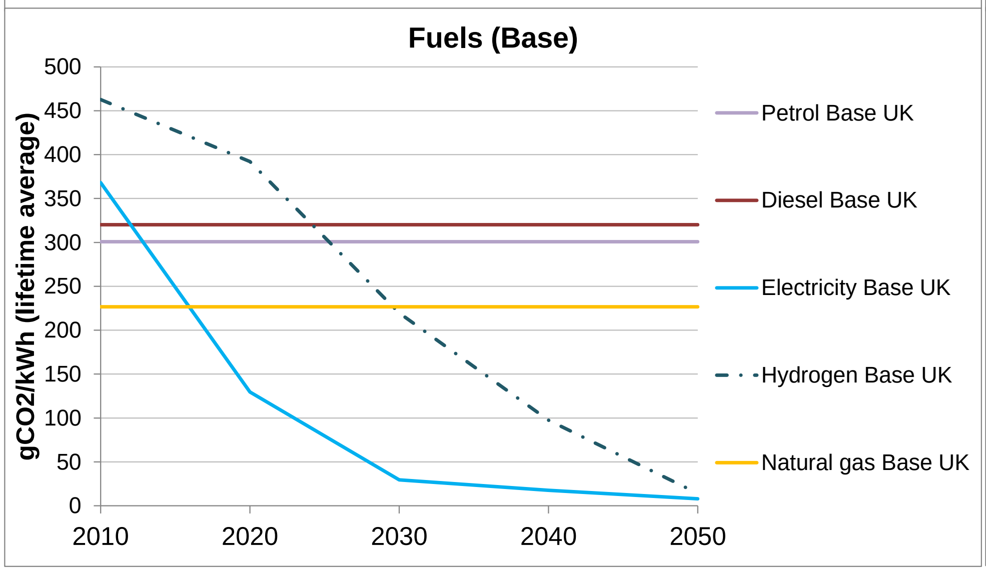
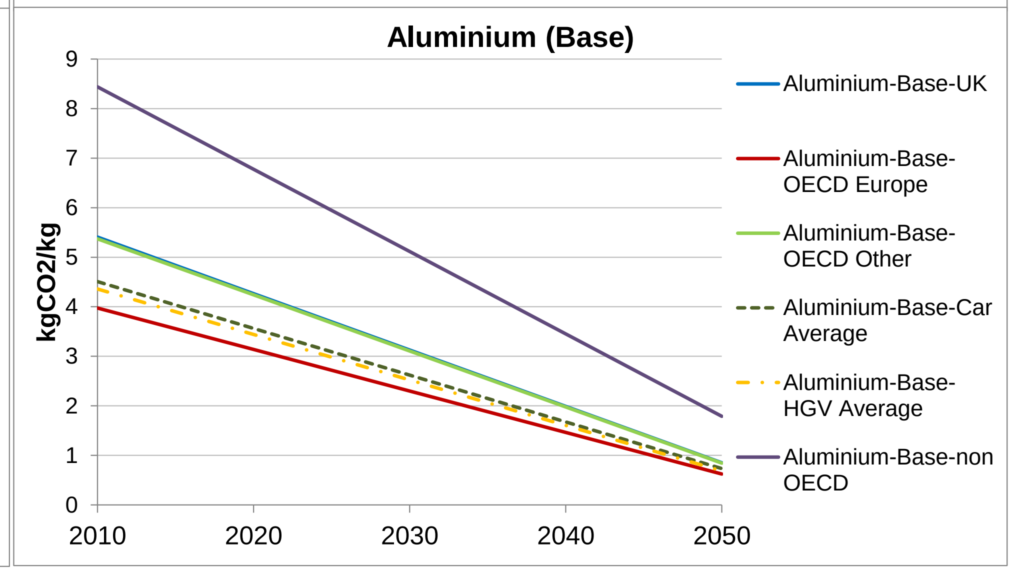






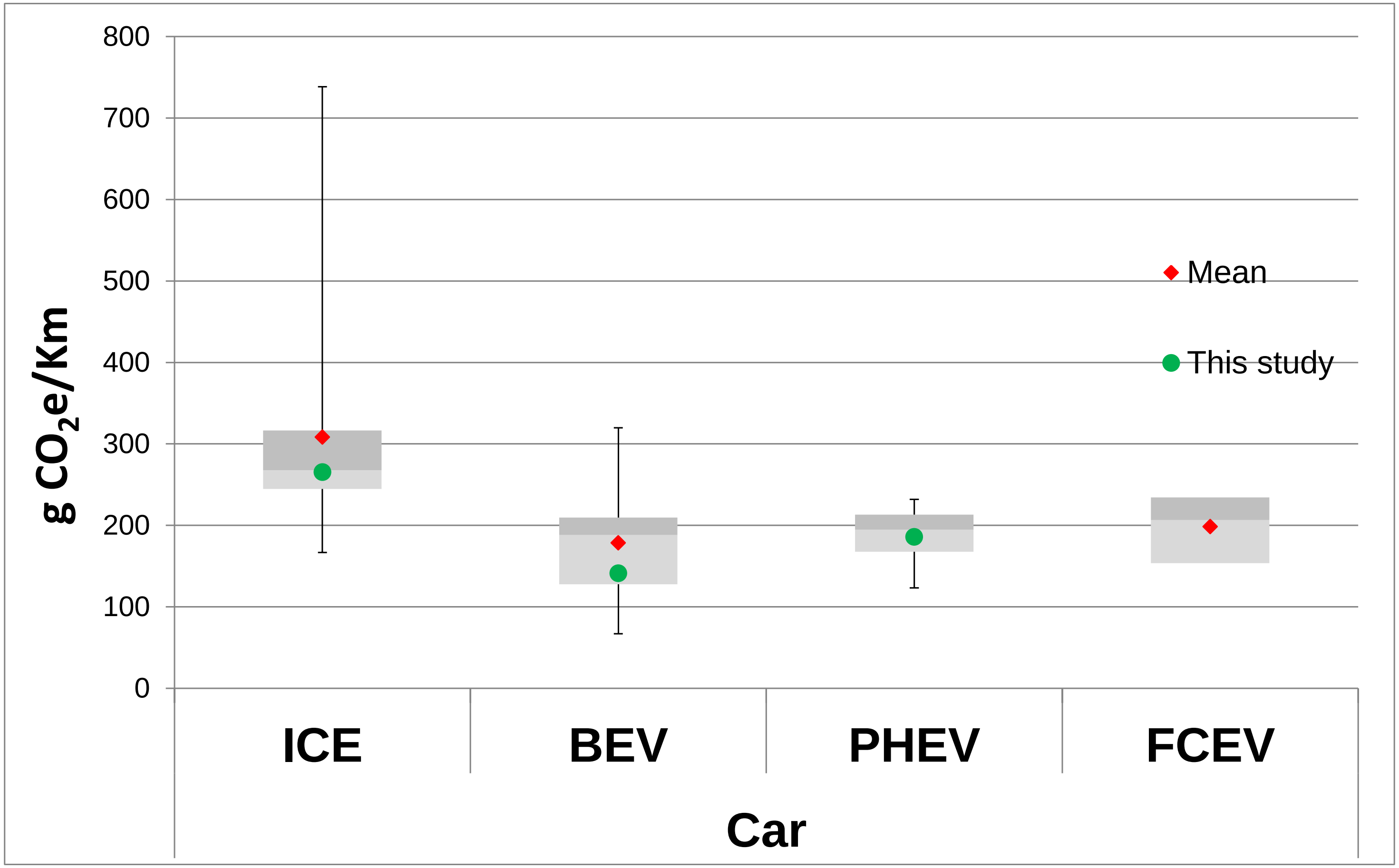


- *Note*: fuel emission factors are well-to-wheel figures averaged over the operational lifetime of a vehicle deployed in a given year.
- The base case assumption is to set recycled content equal to automotive material recycling levels (i.e. > global averages)

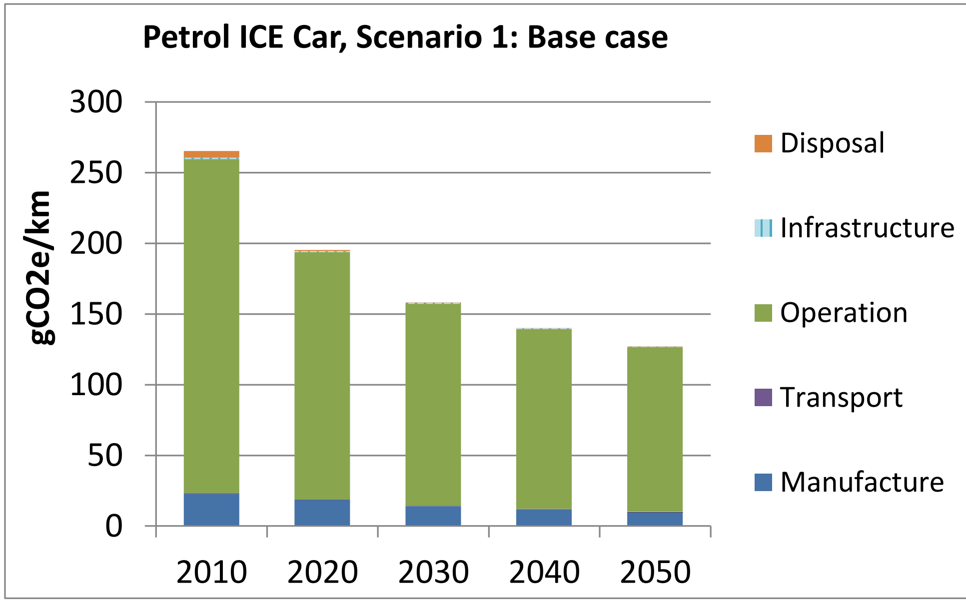
Comparison of base cases to previous studies

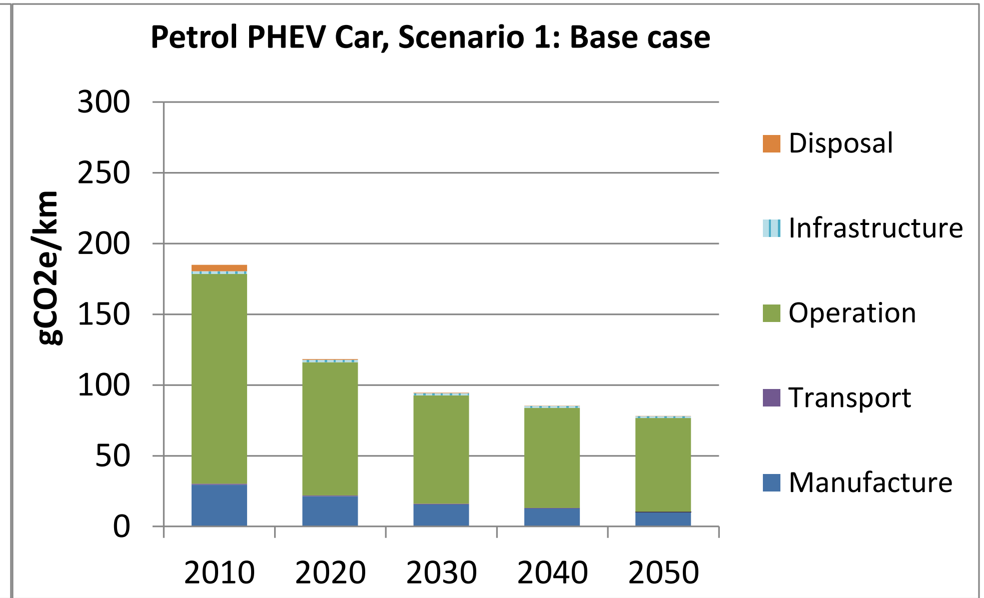
- The estimated current LCEs for the base scenario are: 265 gCO_2e/km for petrol ICE cars (~159gCO_2/km test cycle), 186 gCO_2e/km for petrol PHEV cars and 141 gCO_2e/km for BEV cars.
- Estimated LCEs are at the lower end of the range of LCEs provided by previous studies. This is expected to be principally due to two key differences compared to many of the studies:

1. The higher rates of automotive materials recycling are factored into the recycled content assumptions for materials emission factors
2. For vehicles operating on grid electricity (or hydrogen), the anticipated future (downward) trajectory of the GHG intensity of these fuels has been factored into the operational energy LCE calculations

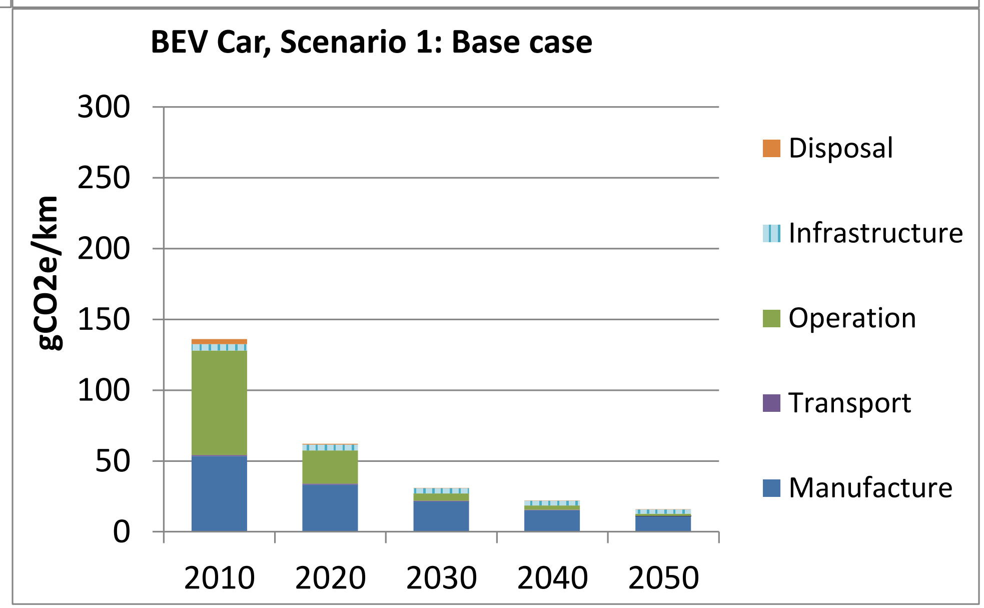


Base case scenario for cars:
Breakdown by lifecycle stage



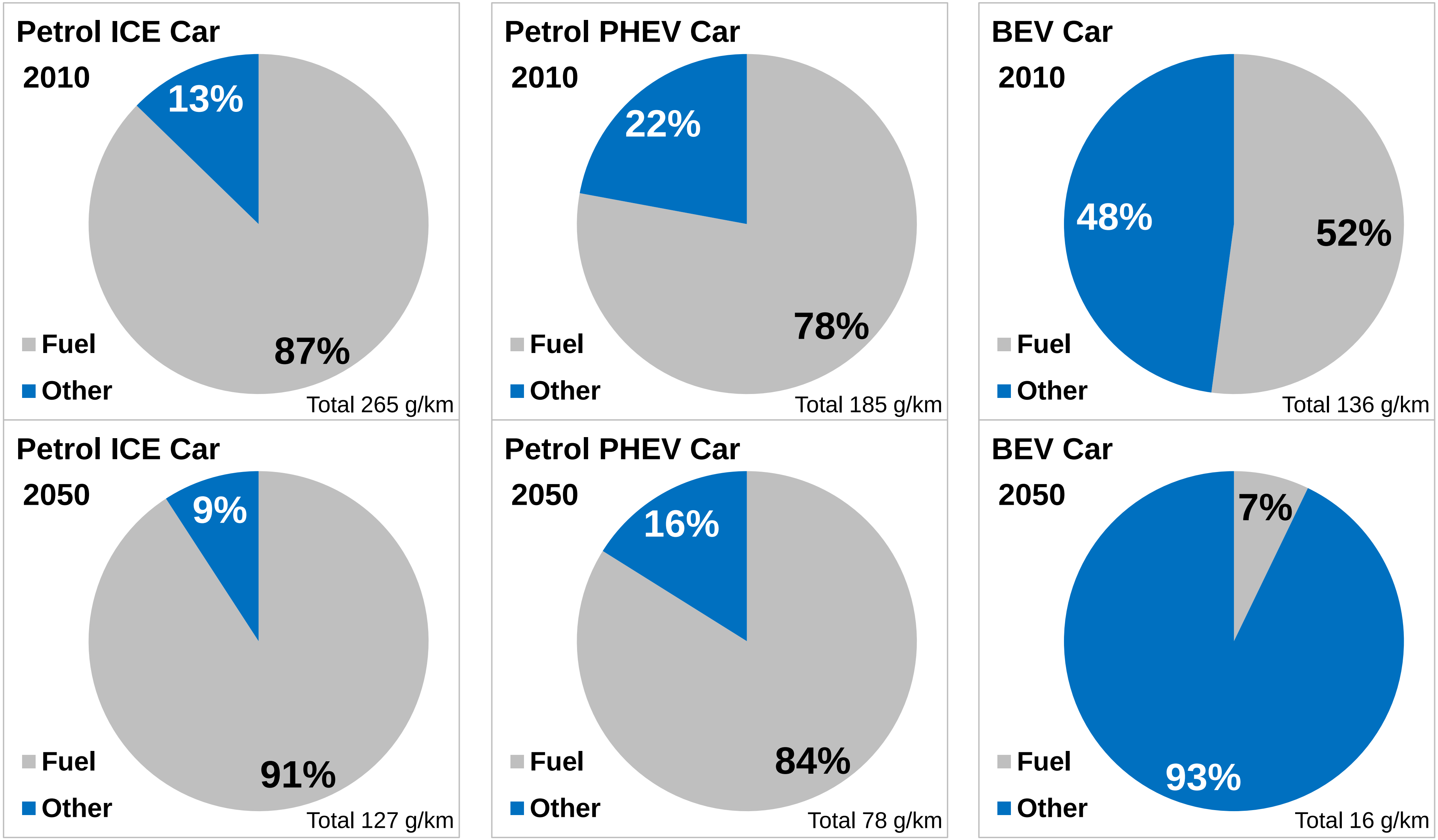


- 2010 petrol car = 159.5 gCO_2/km (test cycle)
- Manufacturing emissions become increasingly important component in future, particularly for BEVs
- Reduced savings from EVs (relative to ICE) - but total LCEs still much lower than for ICE
- Recharging infrastructure a small but still significant component
- 5 gCO_2e/km due to refrigerants in 2010



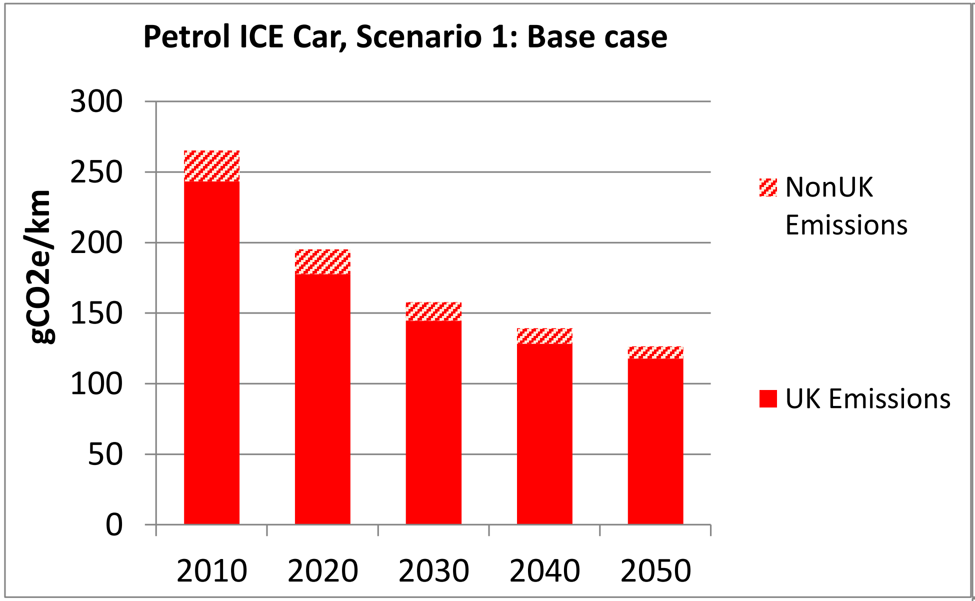
Base case scenario for cars:

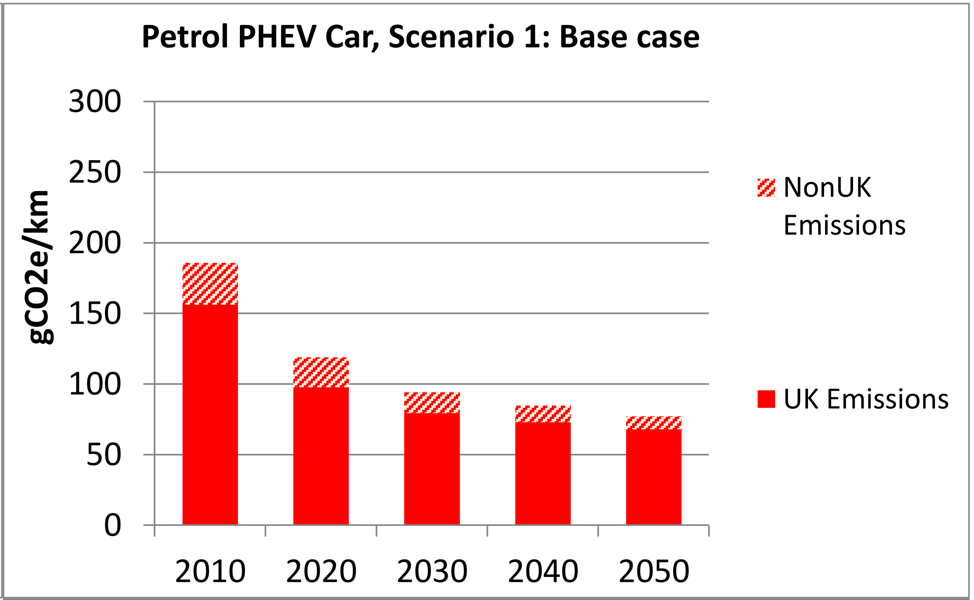
Split of LCE for different powertrains for 2010 and 2050



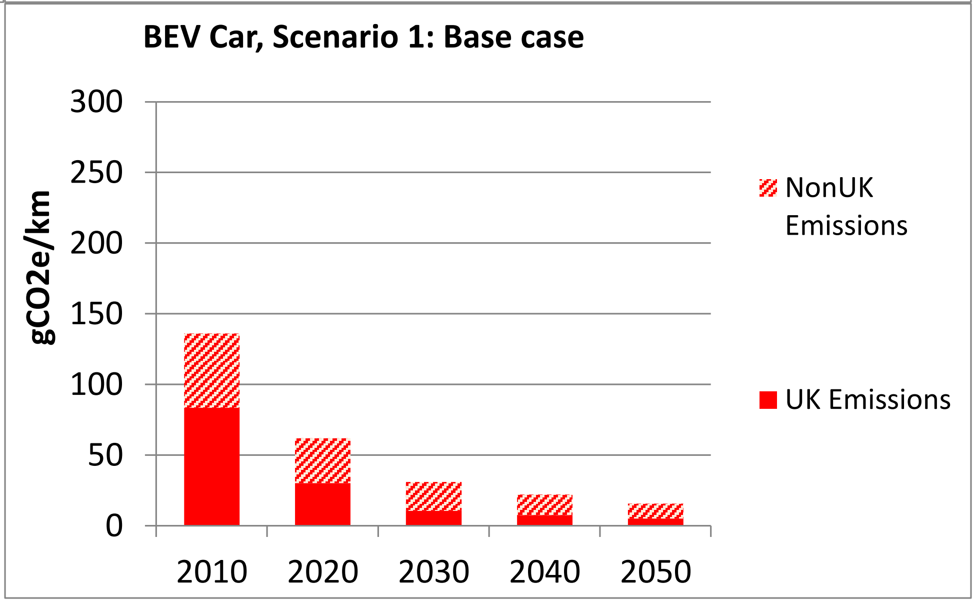
Base case scenario for cars:
Emissions in the UK vs overseas

RICARDO-AEA





- Proportion of emissions outside UK doesn't change much over time for ICE (~8% in 2010) and PHEV (~16% in 2010) technologies
- We estimate that >40% of BEV emissions are outside of the UK in 2010, potentially rising to 66% by 2050 (due to vehicle and battery production)
- In the Worst Case scenario (with very high emissions due mainly to the batteries) over 86% of BEV LCE could occur outside of the UK by 2050 (also due to reduction in operational LCE)



Base case scenario for cars:
Impacts of low and high activity assumptions

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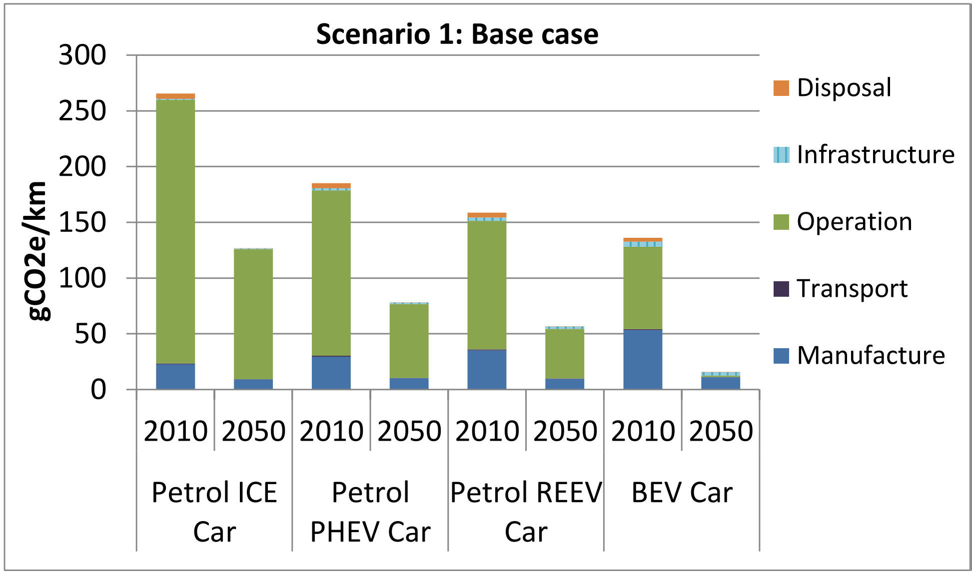
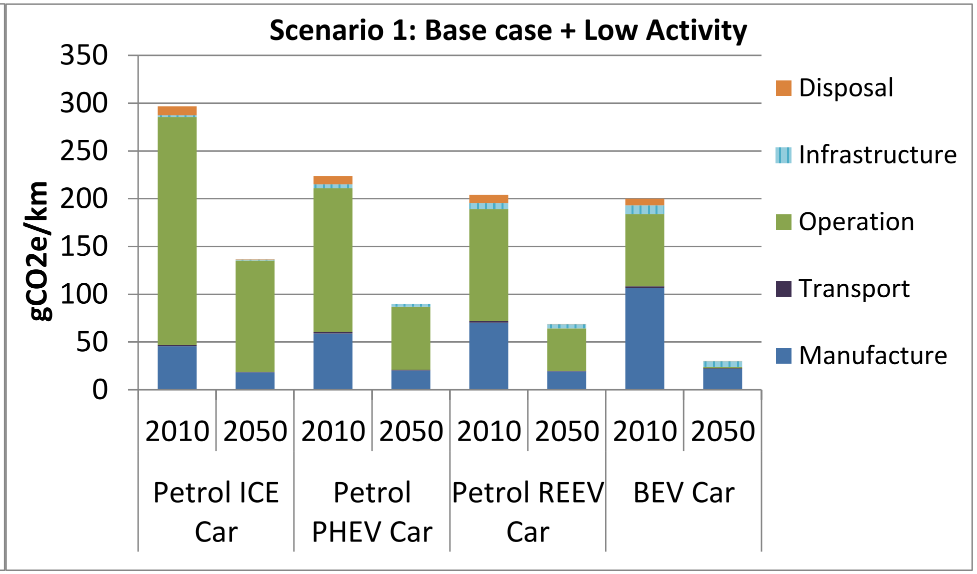
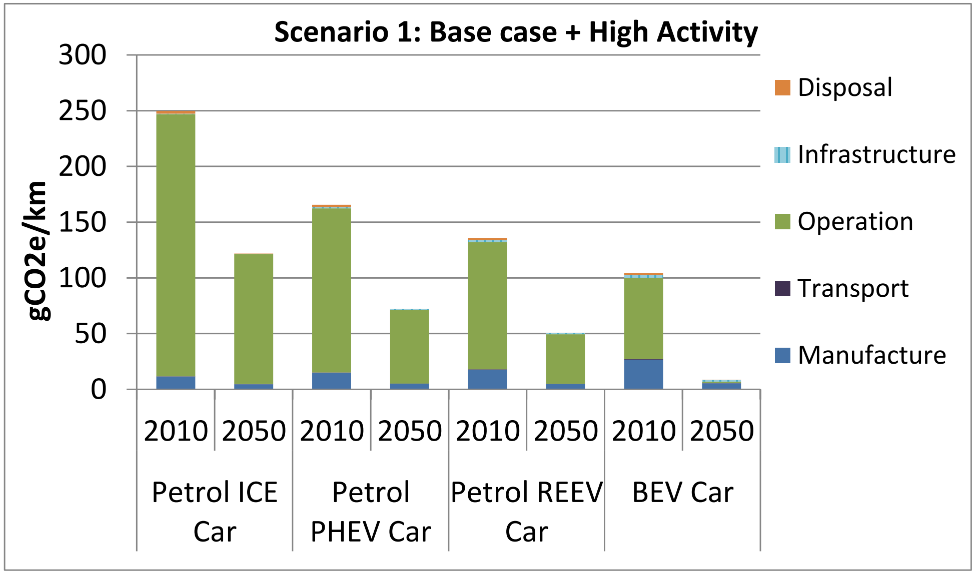




- Under low activity assumptions the reduction in LCE from BEVs vs ICE in 2010 drops from 49% to 33% and in 2050 from 88% to 78%. Under high activity assumptions the reduction improves to 93% for BEV vs base ICE.
- High activity conditions will increase the likelihood of a need to replace the battery within the life of the vehicle, reducing the benefits to an extent (to 92%), [but only significantly in the Worst Case (to 55% by 2050) – see the following pages].



Sensitivity analysis:
Summary list of scenarios

The following elements are the key sensitivities that have been analysed:

- **Scenario 1:** Base Case
- **Scenario 2:** High GHG intensity electricity and hydrogen
- **Scenario 3:** High GHG intensity battery production (factors in high case battery production emission factor and high production energy GHG intensity)
- **Scenario 4:** Compare impact manufacture in UK (versus average regional mix where UK manufacture is 13% for cars, 27% for trucks)
- **Scenario 5:** High vehicle manufacture GHG intensity (for both materials and electricity)
- **Scenario 6:** Assume global average recycling rates for material recycled content
- **Scenario 7:** Battery production is not regional (assume Other OECD)
- **Scenario 8:** Battery replacement in vehicle lifetime (1 per vehicle)
- **Scenario 9:** Best Case (minimum emissions for BEV)
- **Scenario 10:** Worst Case (all BEV high cases combined)
- **Scenario 11:** Best Case + Low Activity (half the base case lifetime km)
- **Scenario 12:** Worst Case + High Activity (double the base case lifetime km)
- **Scenario 13:** H2 FCEV articulated HGVs achieve only 75% of the base case improvement in MJ/km compared to diesel ICE articulated HGVs
- **Scenario 14:** H2 storage takes up twice the weight/volume compared to the base case

Sensitivity analysis: Summary of scenario assumptions

- Scenarios 1 to 10 (from previous slide) are defined below. In addition, scenarios 11-14 (as described on previous page) were also tested.
- "Base" = Baseline assumption; "Alternative" = alternate (usually pessimistic) assumption
- Automotive average recycling rates (set as the default) are significantly higher than the global average recycled content for a number of key materials
- The number of battery replacements in the sensitivity is set to 1 (but can be set as a fraction)

Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Base case	**High GHG electricity /hydrogen**	**High battery GHG intensity**	**UK manufacture**	**High production emissions**
UK Grid electricity (and H2) intensity scenario	Base	**Alternative**	Base	Base	Base
Carbon intensity for material production	Base	Base	Base	Base	**Alternative**
Grid intensity for region of manufacture	Base	Base	Base	Base	**Alternative**
Battery / fuel cell / H2 storage GHG intensity	Base	Base	**Alternative**	Base	Base
Source key materials and components	Average	Average	Average	**UK**	Average
Basis of recycled content assumptions	AutoAv	AutoAv	AutoAv	AutoAv	AutoAv
Basis of battery production assumptions	Regional	Regional	Regional	Regional	Regional
Is replacement battery needed?	No	No	No	No	No

Scenario	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
	Global recycling rates	**Battery production location**	**Replacement batteries**	**Best Case**	**Worst Case**
UK Grid electricity (and H2) intensity scenario	Base	Base	Base	Base	**Alternative**
Carbon intensity for material production	Base	Base	Base	Base	**Alternative**
Grid intensity for region of manufacture	Base	Base	Base	Base	**Alternative**
Battery / fuel cell / H2 storage GHG intensity	Base	Base	Base	Base	**Alternative**
Source key materials and components	Average	Average	Average	**UK**	Average
Basis of recycled content assumptions	**GlobalAv**	AutoAv	AutoAv	AutoAv	**GlobalAv**
Basis of battery production assumptions	Regional	**non OECD**	Regional	Regional	**non OECD**
Is replacement battery needed?	No	No	**Yes**	No	**Yes**

Sensitivity analysis for cars:
Best Case and Worst Case

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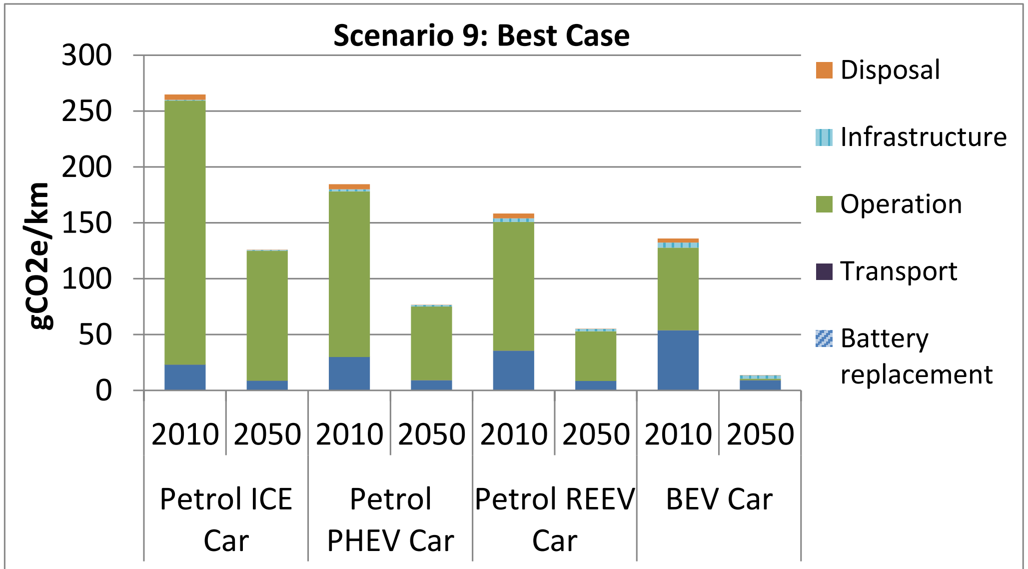
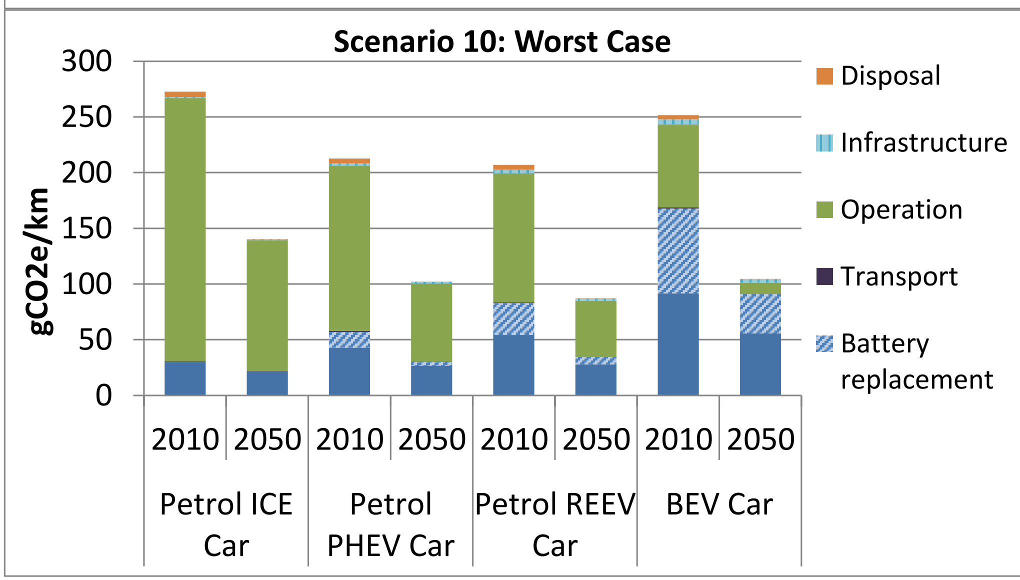
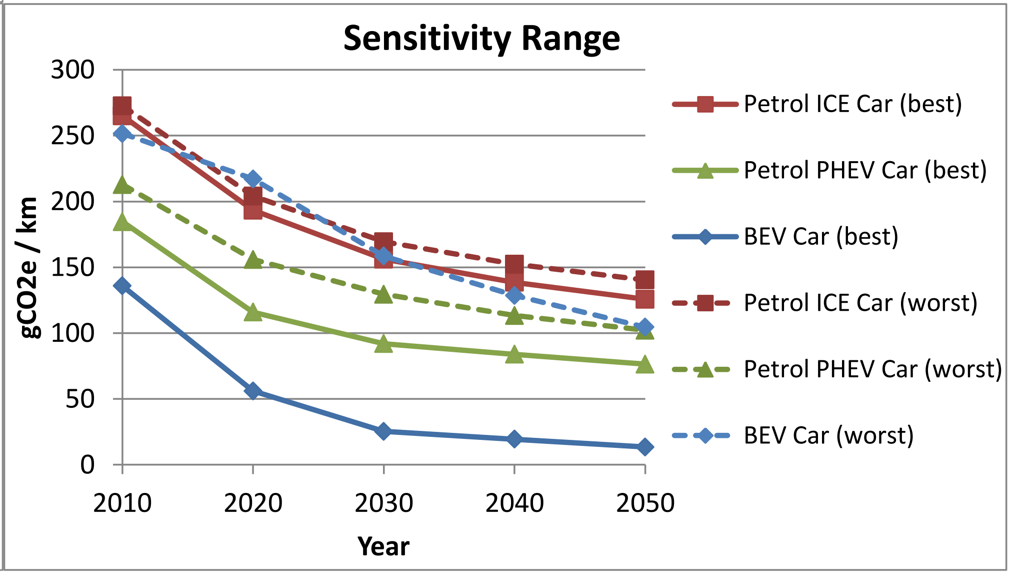


- Battery developments are critical to achieve the maximum savings potential
- In worst case BEVs achieve only 26% reduction on base ICE in 2050 (excluding the potential impact of biofuels in ICEs). However, battery replacement seems unlikely under current lifetime km assumptions in comparison with current manufacturer warranties
- BEVs show 55% improvement over base ICE in 2050 for more realistic alternate worst case + high lifetime km scenario





Sensitivity analysis for cars:
Comparison of different scenarios for BEVs

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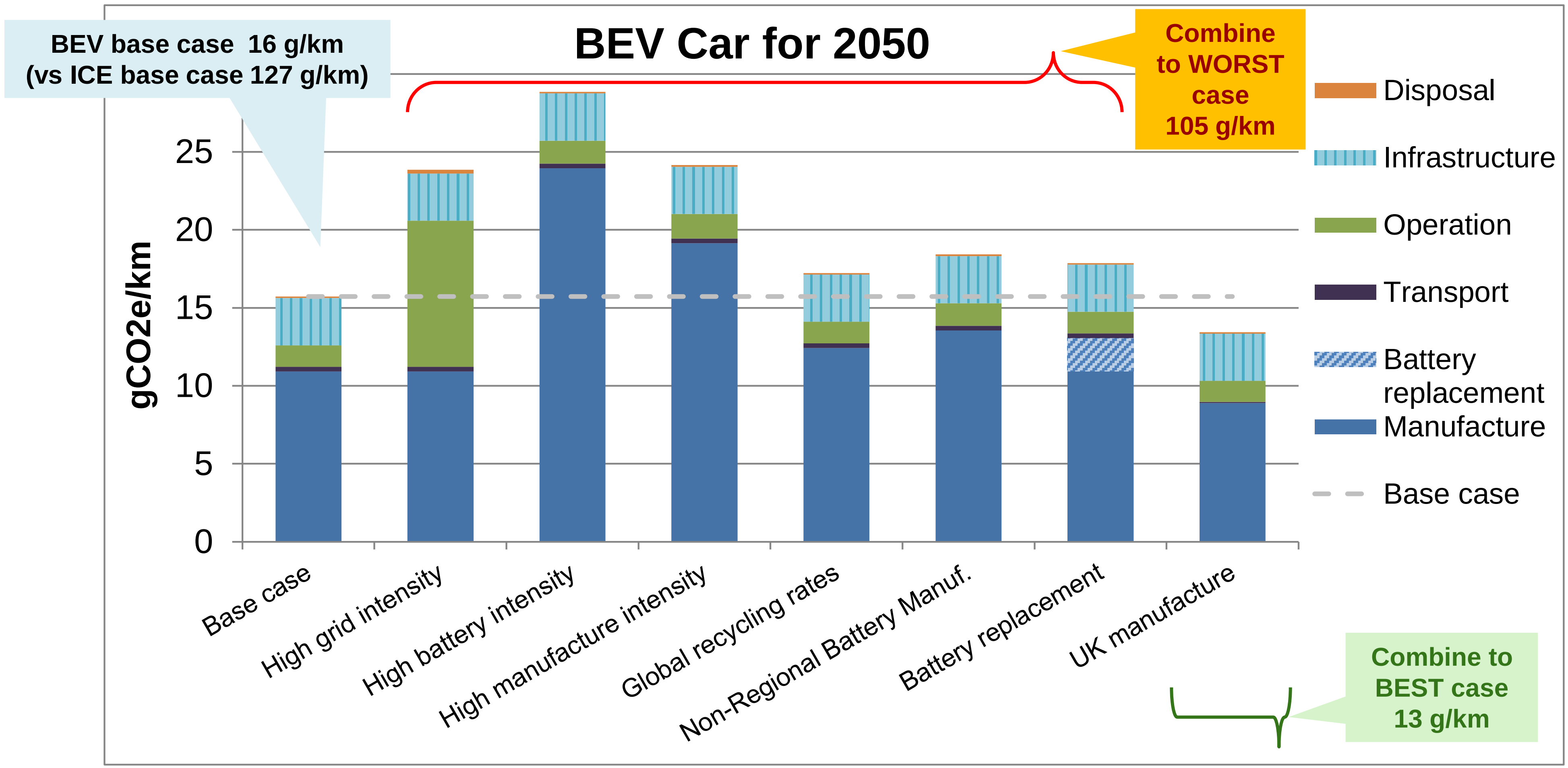
- Individual sensitivities show BEVs reducing GHG life cycle emissions by 77%-89% vs ICE in 2050
- Worst case improvement (combined negative impacts) is 26% reduction compared to ICE base case (excluding any potential savings from biofuel use), but battery replacement appears very unlikely at base case 8,000 mi/yr; Worst case BEV LCE at 16,000 mi/yr = 57 g/km, -55% on ICE



Base case and sensitivities for artic HGVs

Breakdown by lifecycle stage, best and worst cases

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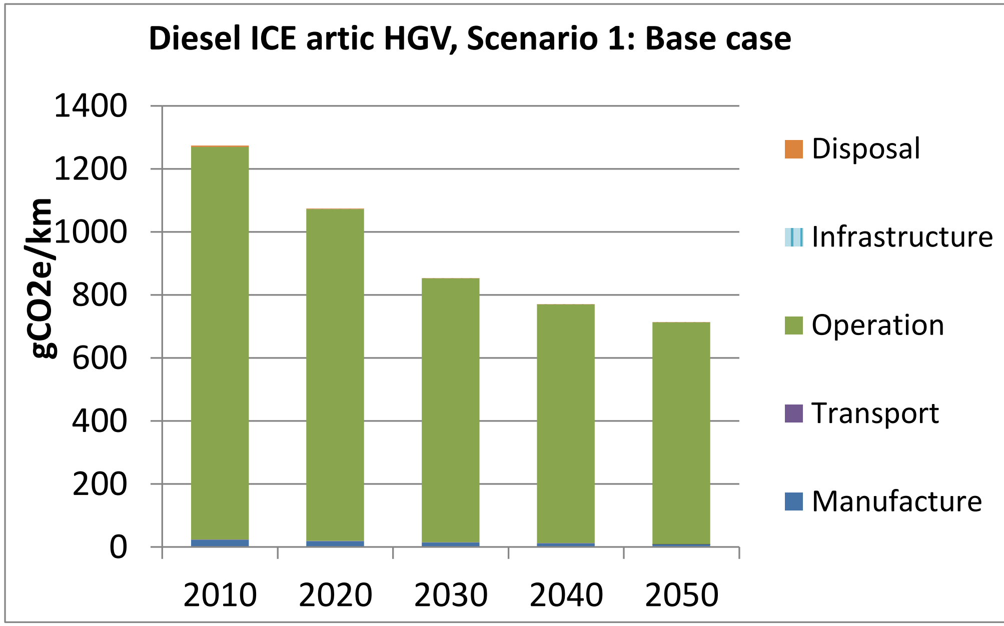
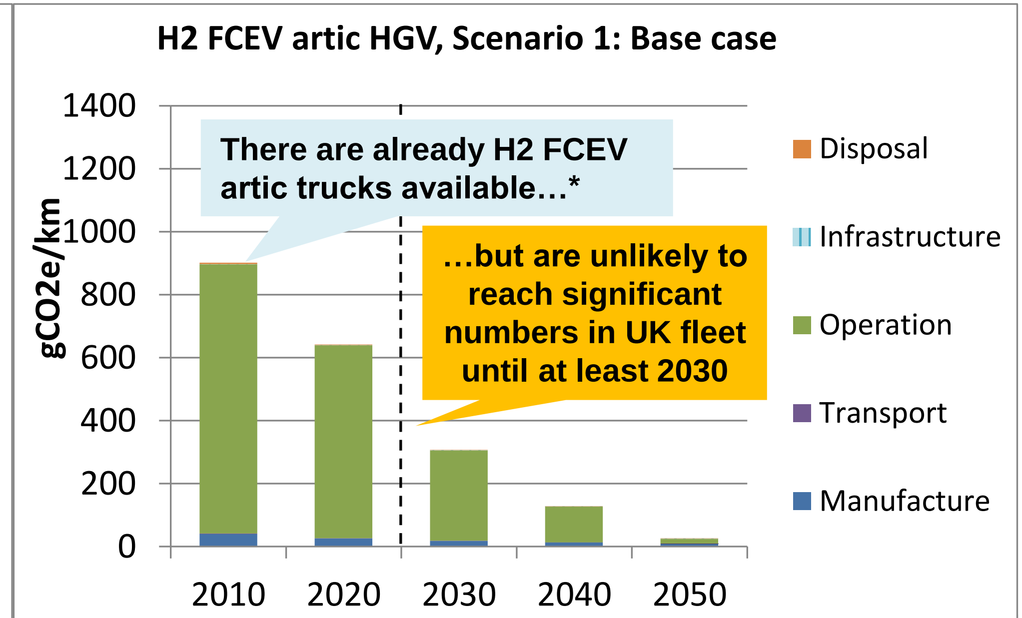
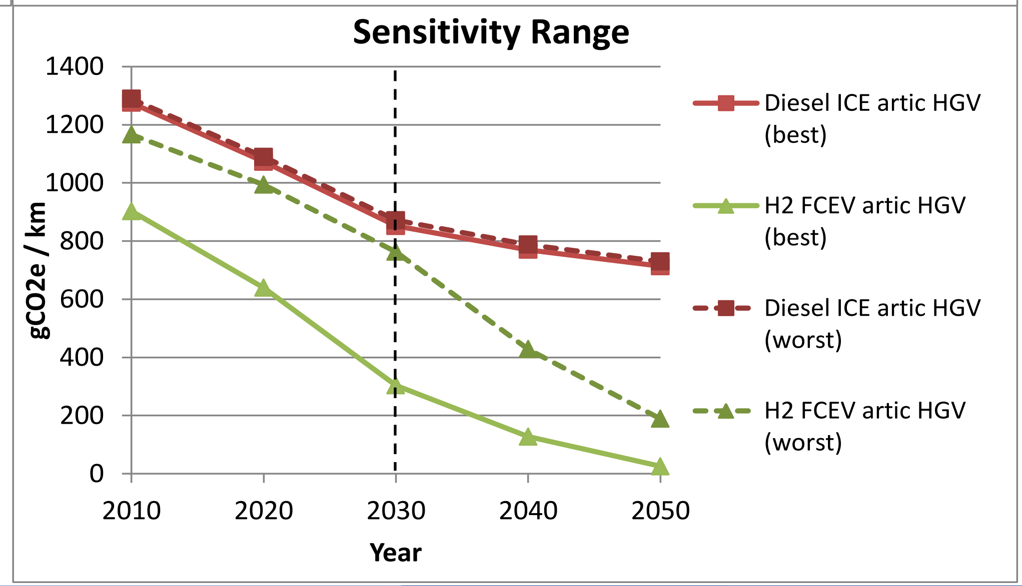




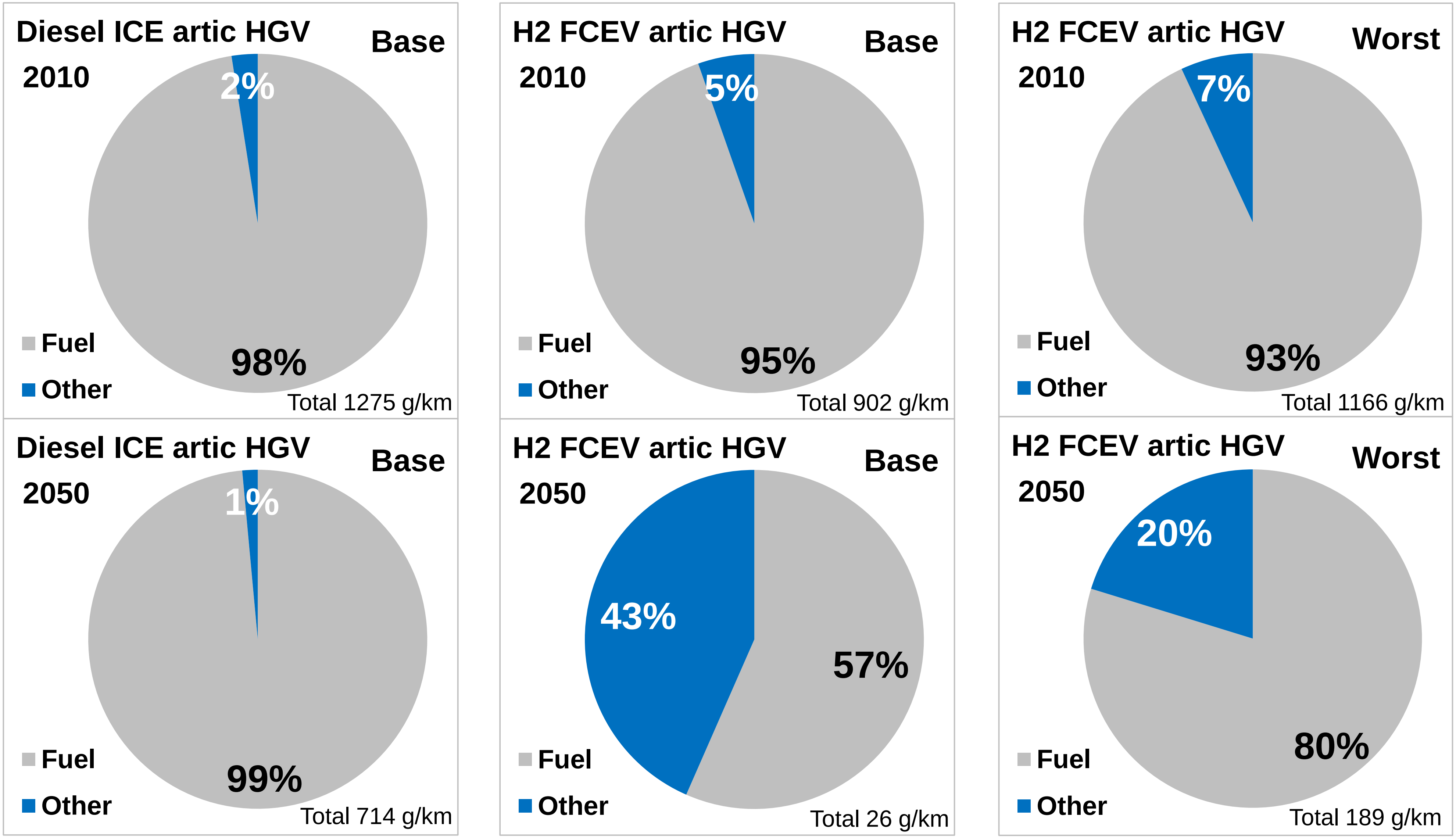
- Operational emissions dominate for both technologies
- Hydrogen production GHG and FCEV efficiency are the key to savings compared to base ICE
- The impacts of additional emissions from manufacturing and hydrogen refuelling infrastructure may be relatively minimal components except in the very long term (further work is needed to better quantify these)



* For example: www.visionmotorcorp.com/tyrano.asp

Base case for artic HGVs:

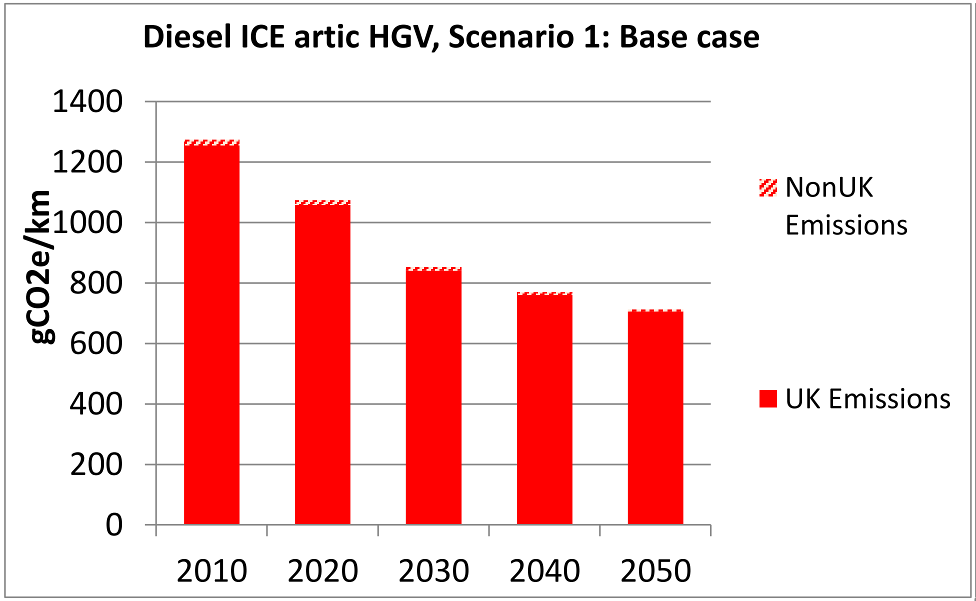
Split of LCE for different powertrains for 2010 and 2050

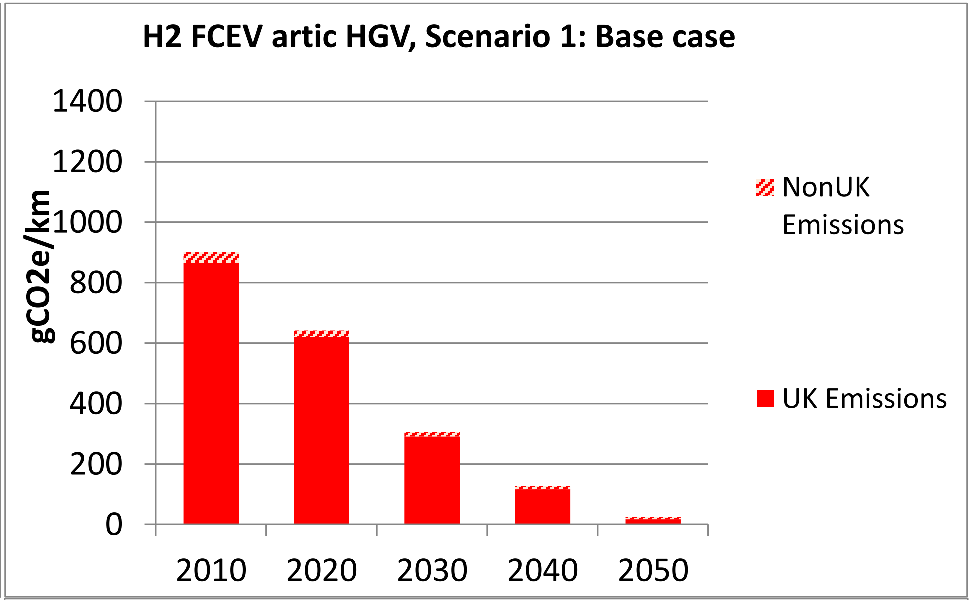


- The majority of emissions are due to fuel use, though reduced for FCEV in 2050 (at base H_2 intensity)

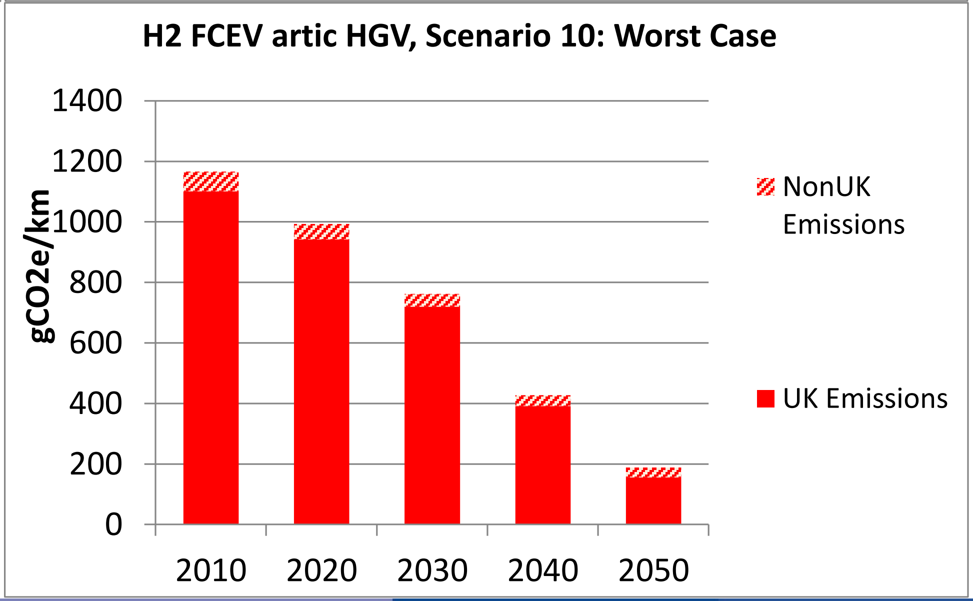
Base case for artic HGVs

Emissions in the UK vs overseas





- Assuming hydrogen production occurs in the UK, almost 98% of lifecycle emissions would be expected to occur in the UK for both Diesel ICE and 96% for H2 FCEV articulated HGVs. This share does not alter appreciably in the long-term for ICEs in the Best or Worst Case scenarios (to 99% and 97% respectively). For H2 FCEVs the share decreases to 2050 to 69% for the Base Case and 83% for the Worst Case scenario.



Base case for artic HGVs

Impacts of activity, FCEV efficiency and H2 storage assumptions

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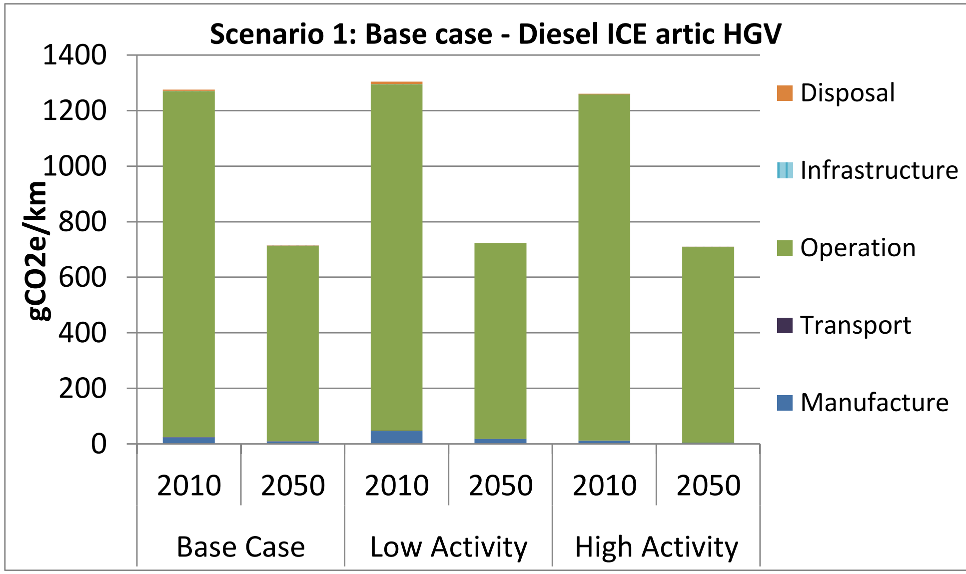
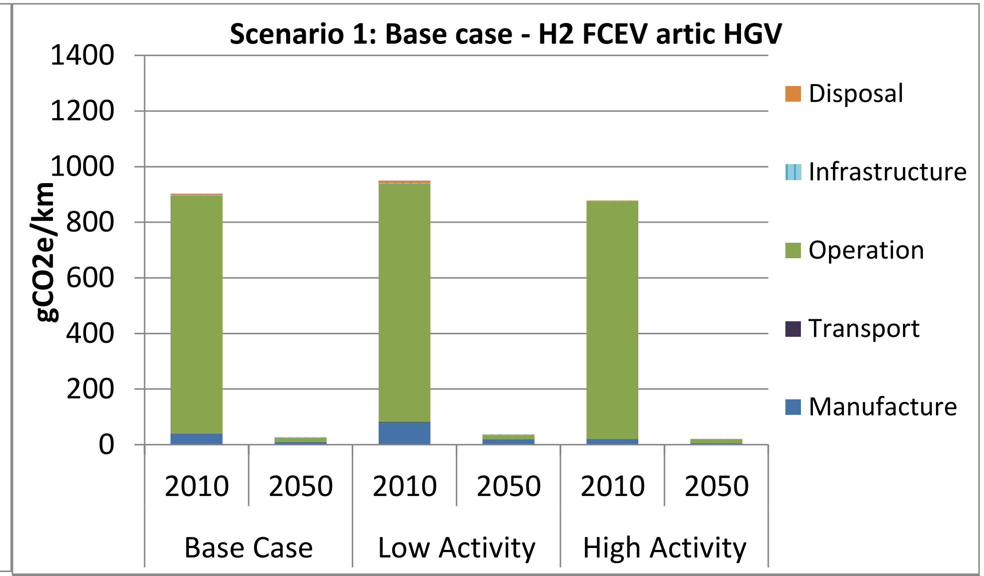
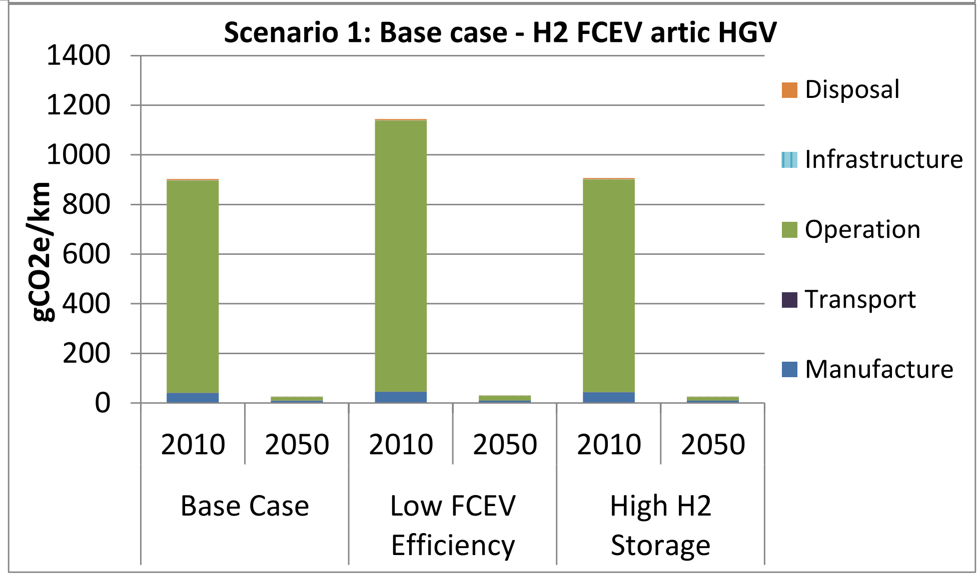




- In the peer review, SMMT recommended consistency with recent work on HGVs for the LowCVP (2012) and a sensitivity on activity.
- Sensitivities were therefore carried out on halving or doubling the default assumption on lifetime activity (= 74,000 miles/yr). However, these show little impact on emissions per km, since these are dominated by operational energy use.
- Reducing the FCEV efficiency improvement over ICE (by 25%) has the biggest impact in the short-/ mid-term; little in the long term at base H_2 intensity
- Doubling the H_2 storage has little impact on LCEs



Conclusions:
Part 1 – Passenger Cars

RICARDO-AEA

- For the base scenario, the average total life cycle emissions of a ‘2010’ vehicle were estimated to be 265 gCO_2/km for petrol ICEs (with regulatory ‘test cycle’ equivalent direct emissions of ~159 gCO_2/km), 186 gCO_2/km for petrol PHEVs and 141 gCO_2/km for BEVs.
- The sensitivity analysis highlighted that battery developments are critical to achieve the maximum GHG savings potential for BEVs (and REEVs, PHEVs to a lesser extent), for example:
  - Improvements in battery cycle/lifetime durability to minimise the likelihood of replacements in vehicle lifetime
  - Improvements in battery energy density to reduce material use
  - Improvements in recycling practices to generate savings
  - Regional (UK/European) battery production to minimise GHG
  - Other improvements in battery manufacture GHG intensity (i.e. in production energy and materials used)
- However, in the worst case scenario with high lifetime km (requiring one battery replacement), BEVs still have almost 44% reduction on the base case ICE by 2050 (excluding any biofuel use with ICEs beyond the current average blend levels found in UK refuelling stations).
- The future non-UK emissions share appears unlikely to increase much for ICE (~9%) and PHEV (~18%), but could increase significantly for BEV (currently 41%, potentially rising to 66% by 2050). This is due primarily to a significant reduction in operational and other UK emissions components.
- Recharging infrastructure is a small but still significant component (>3% for BEVs in 2010), but could be potentially much more significant in longer term (possibly as high as 20%). Again, this is due primarily to a significant reduction in other emission components. Further research is needed to quantify the relative impacts of different infrastructure types/mixes and likely 2050 requirements.

Conclusions:
Part 2 – Articulated HGVs

- For the base scenario, the average total life cycle emissions of a '2010' vehicle were estimated to be 1275 gCO_2/km for diesel ICEs, and 902 gCO_2/km for H2 FCEVs. These drop to 714 gCO_2/km for diesel ICEs and 26 gCO_2/km for H2 FCEVs by 2050.
- Operational emissions (i.e. in the UK) dominate for both ICE and FCEV technologies – so reducing hydrogen production GHG emissions will be key to achieving savings for potential future FCEVs
- Due to the very high operational lifetime km of artic HGVs, sensitivities on lifetime km in combination with other areas (e.g. production intensity, fuel cell intensity, etc) had little effect on the overall results in the long-term (other than the GHG intensity of hydrogen production). In the short- to mid-term, sensitivities on FCEV efficiency had a more significant effect on overall emissions.
- Since H2 FCEV trucks are only just being introduced to the marketplace, there is a fair degree of uncertainty on their performance relative to diesel ICEs. The baseline assumptions used in this study for H2 FCEV trucks are based on the scaling up of information from light duty vehicles. Sensitivities carried out on the efficiency improvement of FCEV trucks over diesel ICEV equivalents illustrate that in the short- to mid-term this has a significant impact on their LCEs. As indicated already, in the long-term the GHG intensity of hydrogen production dominates.
- A sensitivity on the assumptions on hydrogen storage (i.e. doubling how much of the vehicle's payload is taken up) show relatively little impact on the result.

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ANNEX

Transport Technologies:
Additional Modelling Assumptions

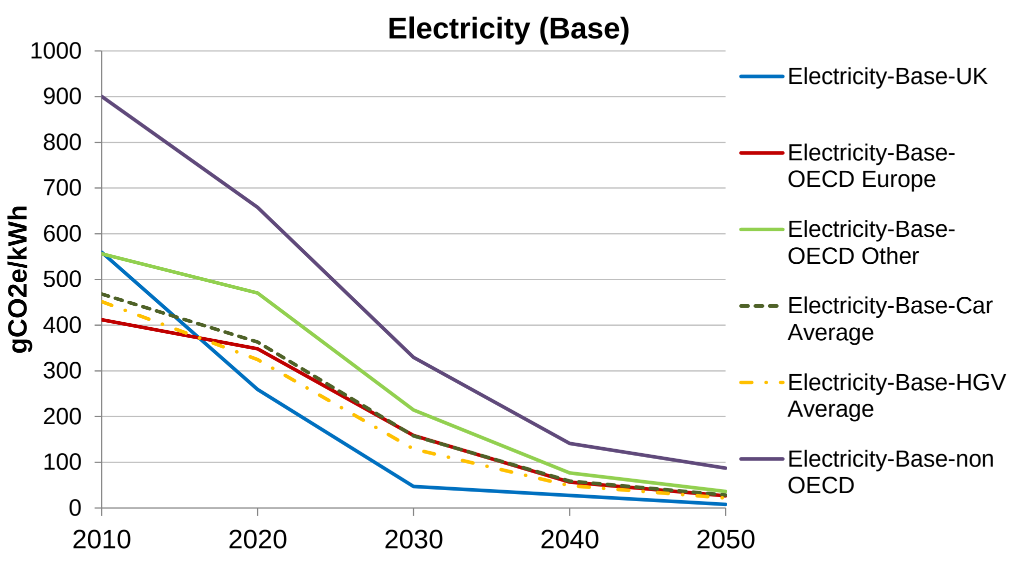
Additional modelling assumptions for transport:
Energy and Materials GHG intensity, part 1

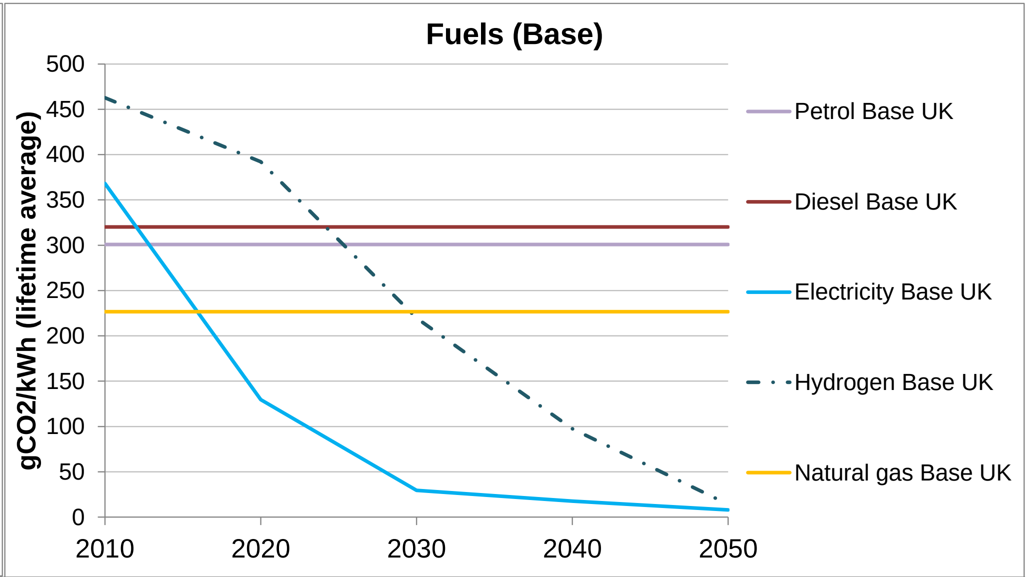
- **Freight transport:** current g/km EFs (for transport of vehicles from their places of manufacture to market) for ship, rail, and road transport were based on SimaPro; a gradual improvement over time was assumed, reaching 50% improvement by 2050.
- **Electricity:** UK based on CCC modelled data, NonUK based on IEA ETP 2012: both scaled up to include transmission & distribution losses and upstream emissions based on data from Defra/DECC GHG Conversion Factors for Company Reporting (2012)
- **Hydrogen:** emissions estimated based on linear change from production from gas in 2010 to electrolysis of grid electricity in 2050. Assumes conversion efficiency of 70% in 2010 rising to 80% in 2050, and 30% energy loss factor for conversion into liquid H_2.
- **Fuels (operation):** petrol and diesel set to current emission factors – flat to 2050 (i.e. excluding effects of potential increases in biofuel use). Emission factors for electricity and hydrogen calculated as averages over the vehicles operational life (e.g. for 2010 BEV, 14 years = average of EFs between 2010 and 2023).
- **Steel (plus iron, HSS):** uses IEA ETP (2012) values for steel; values for iron and high-strength steel scaled based on relative values from the Bath ICE database (2011)
- **Aluminium:** estimated based on data from IEA ETP (2012).
- **CFRP & GFRP:** Values for Europe from Bath ICE database (2011) for 2010. Assume ~50% of emissions due to manufacturing energy. Materials component scaled relative to plastics (base polymer material is also used in plastics) to estimate other data values by region and year. Energy component scaled relative to electricity intensity.
- **Cu, Zn, Pb, Mg, Glass:** Values for Europe from the Bath ICE database (2011) for 2010. These were scaled relative to steel to estimate other data values by region /year.
- **Plastics:** base values for different plastics sourced from the Bath ICE database (2011). Average emission factor estimated based on % share in average car according to JRC IPTS (2008/9) data in European TREMOVE model. Assumed production intensity improvement to 2050 based on estimates provided by CCC for the UK plastics industry.
- **Others:** base values were sourced from the Bath University's ICE database and an assumed production intensity improvement of 30% by 2050 was used in base case, and 15% by 2050 in the alternative case.

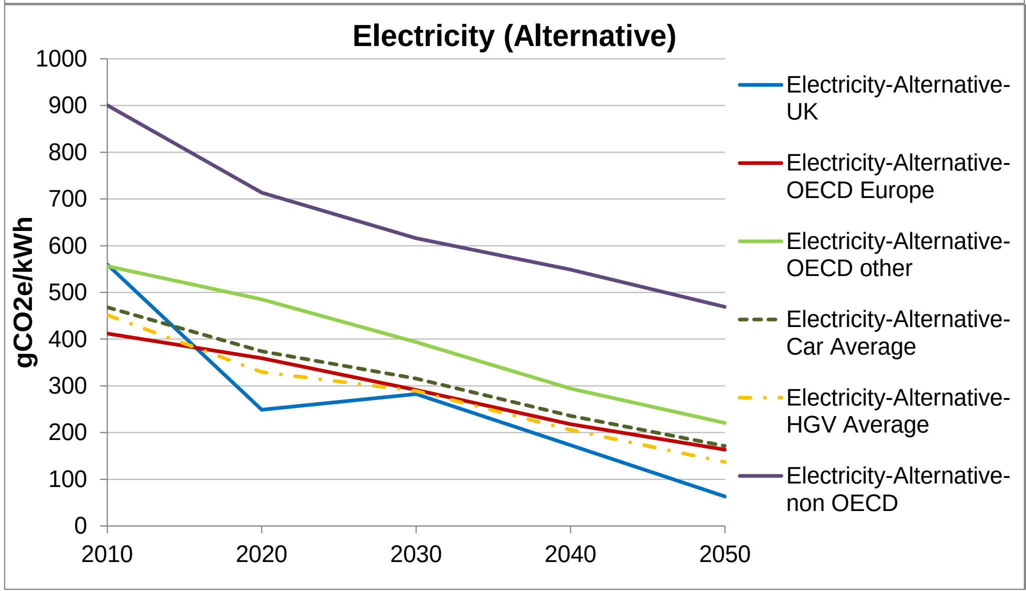
Additional modelling assumptions for transport:
Energy and Materials GHG intensity, part 2

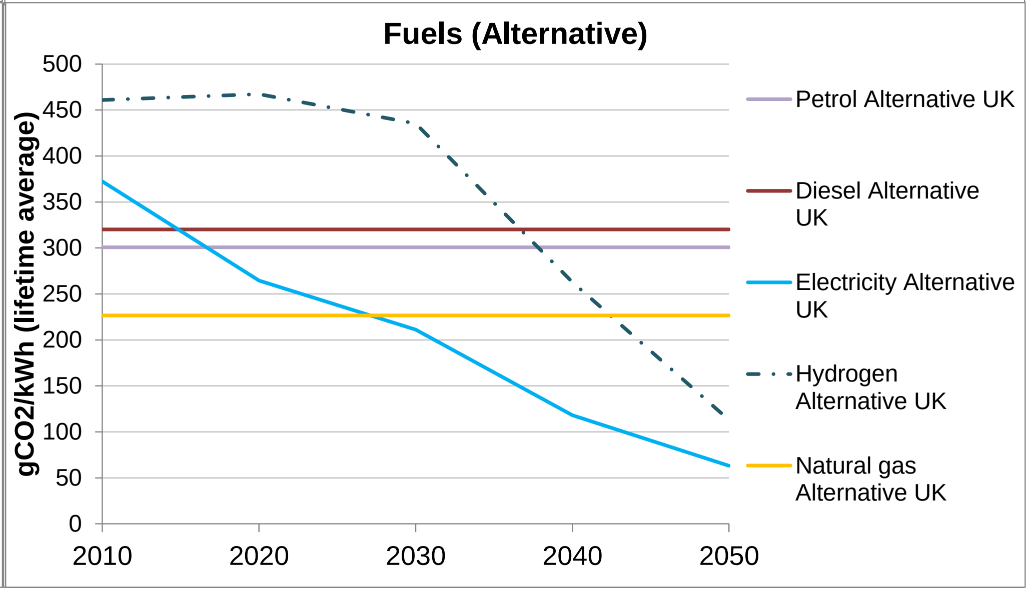
- **Automotive recycling:** current (2010) and future (2020) recycling rates for different materials were based on JRC IPTS (2008/9) data in the European TREMOVE model, which factor in current practice and increased future recycling requirements under EC ELV Directive.
- **Batteries:** Patterson et al. (2011) average and high case values used for base and high case assuming manufacturing in E Asia. Estimated 35% of emissions due to manufacturing energy consumption. Energy and materials components were estimated separately for different regions and years based on electricity (for energy) and steel (for materials, in the absence of a better alternative). Future improvement due to reduced materials use (via greater energy density) also factored into future trajectory for materials component.
- **Fuel cells:** Base fuel cell emissions for low and high case based on Lucas et al. (2011) assuming manufacturing in E Asia. Estimated 35% split of emissions due to manufacturing energy consumption. Energy and materials components estimated separately for different regions and years based on electricity (for energy) and steel (for materials).
- **H2 storage:** Base H_2 storage emissions for low and high case based on Lucas et al. (2011) assuming manufacturing in E Asia. Estimated 35% split of emissions due to manufacturing energy consumption. Energy and materials components estimated separately for different regions and years based on electricity (for energy) and aluminium (for materials).
- **Split of UK and Non-UK materials and manufacturing emissions:** these were estimated according to the selected region (car average = 13% UK, HGV average = 27% UK). Non-UK manufacture is assumed to be essentially 100% non-UK emissions. For UK manufacture it is assumed that 45% of steel and 27% of aluminium is produced in the UK (Dahlström et al, 2004). In the absence of other information it is assumed 20% of other materials used in UK vehicle manufacture are also produced in the UK.

Additional modelling assumptions for transport:
Energy and Materials GHG intensity, charts 1





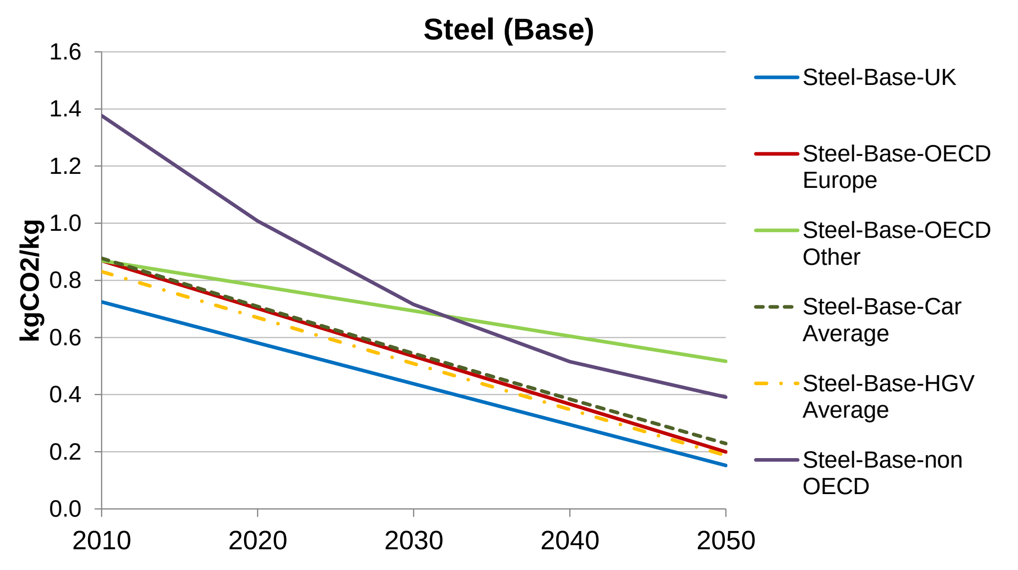


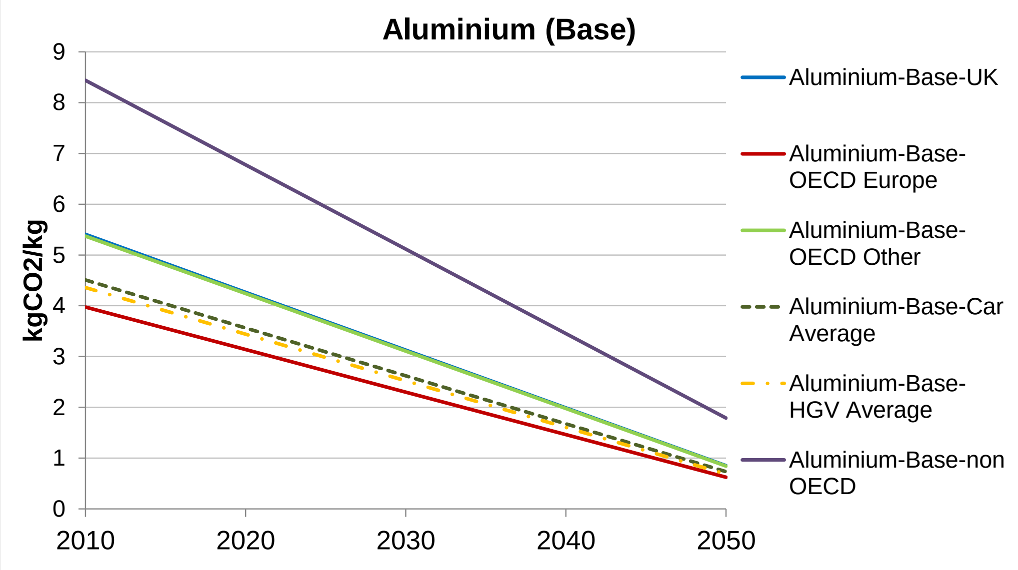


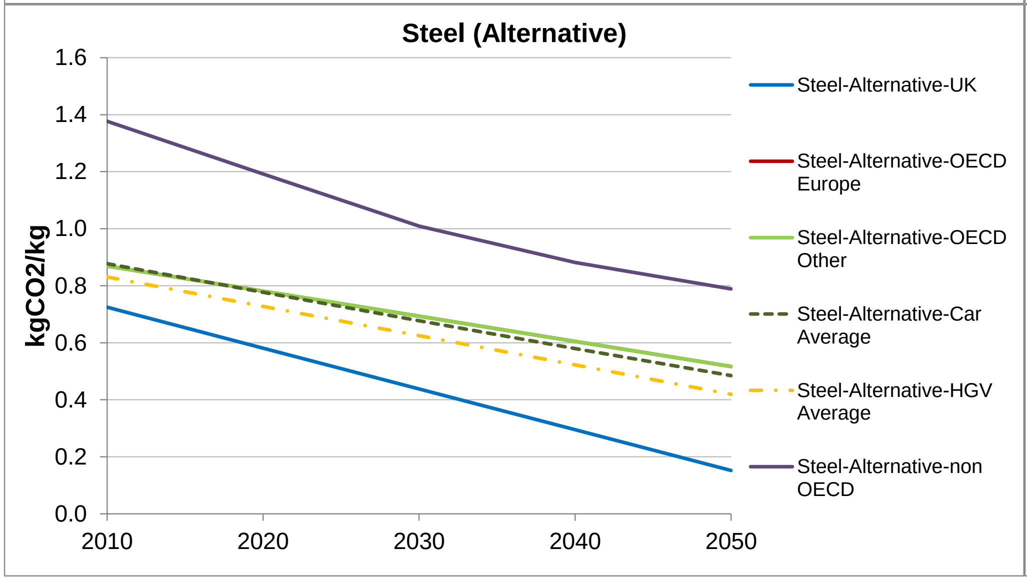
- *Note*: fuel emission factors are well-to-wheel figures averaged over the operational lifetime of a vehicle deployed in a given year.

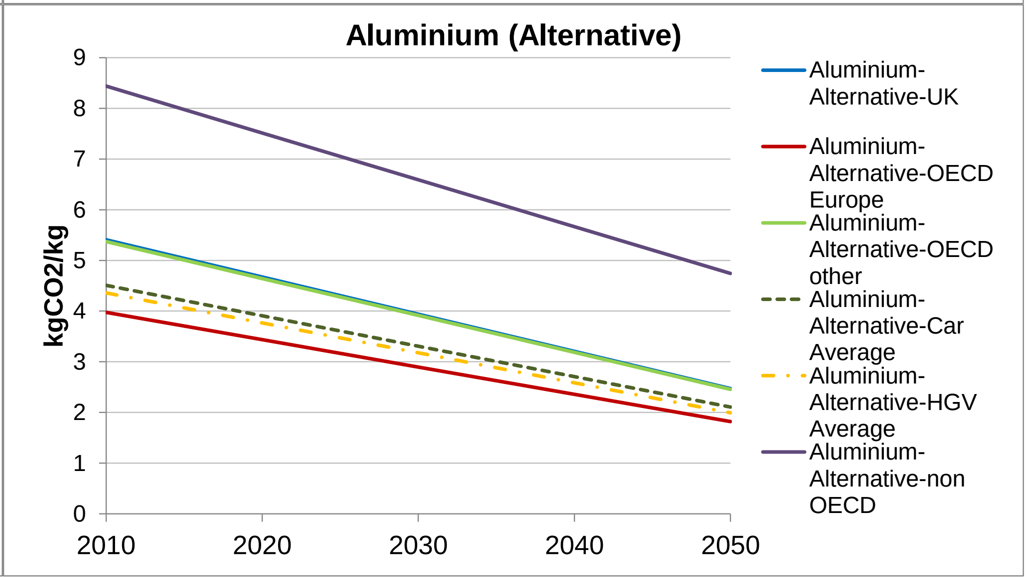
Additional modelling assumptions for transport:

Energy and Materials GHG intensity, charts 2





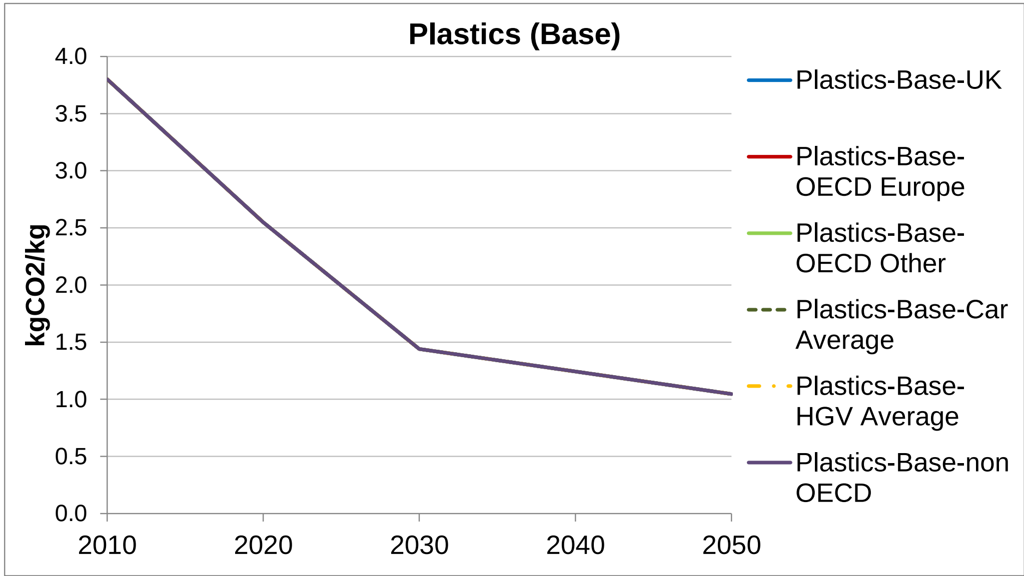


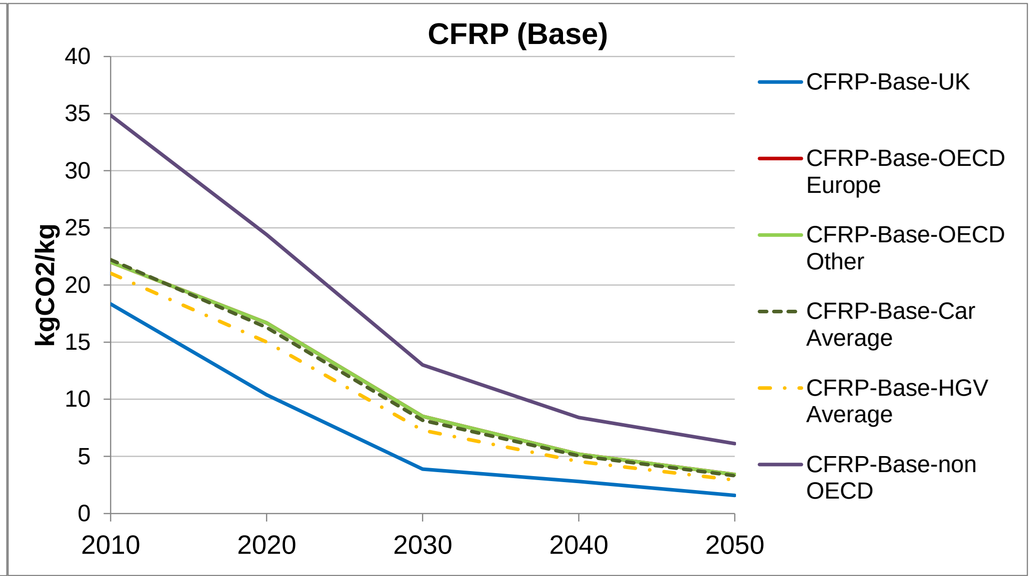


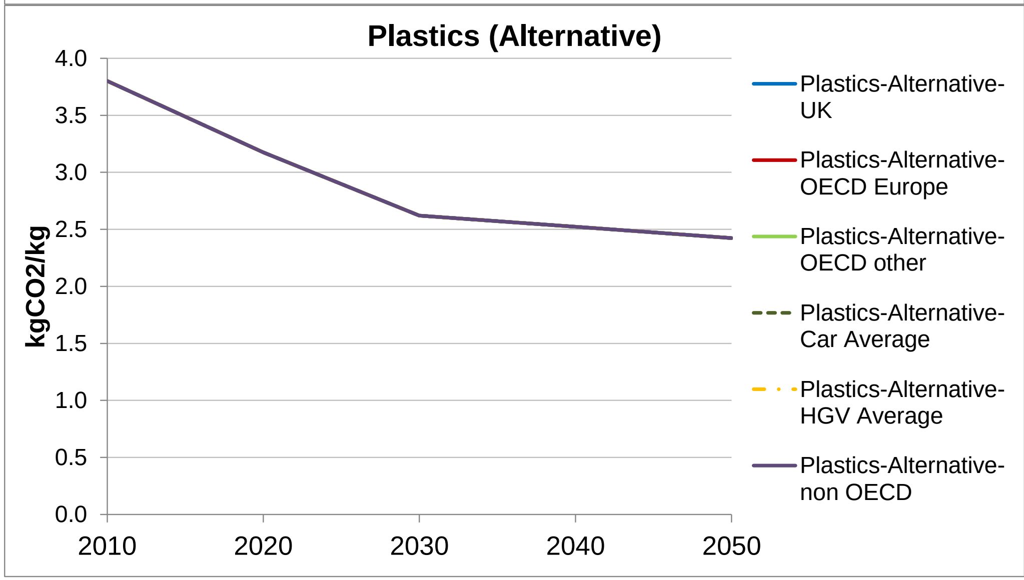
- For automotive rates of recycling (Al = 63%, Fe = >90%), which are greater than global av. (Al = 33%, Fe = 39%)

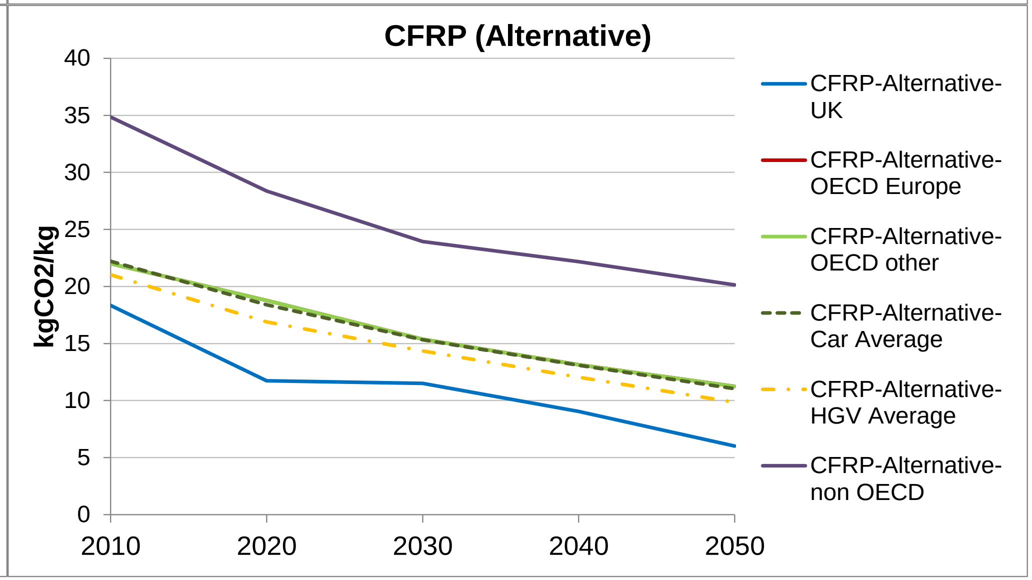
Additional modelling assumptions for transport:

Energy and Materials GHG intensity, charts 3

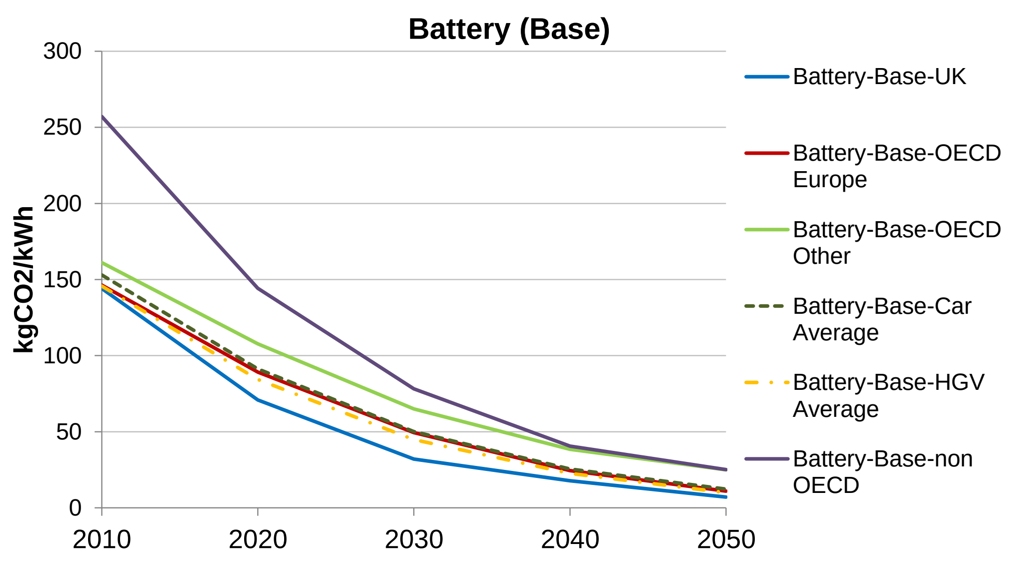


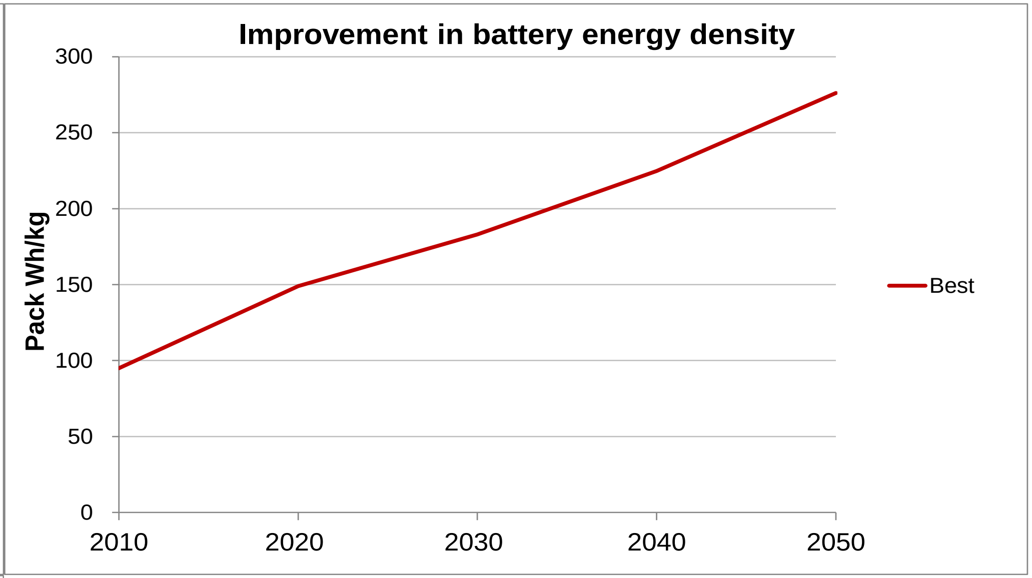


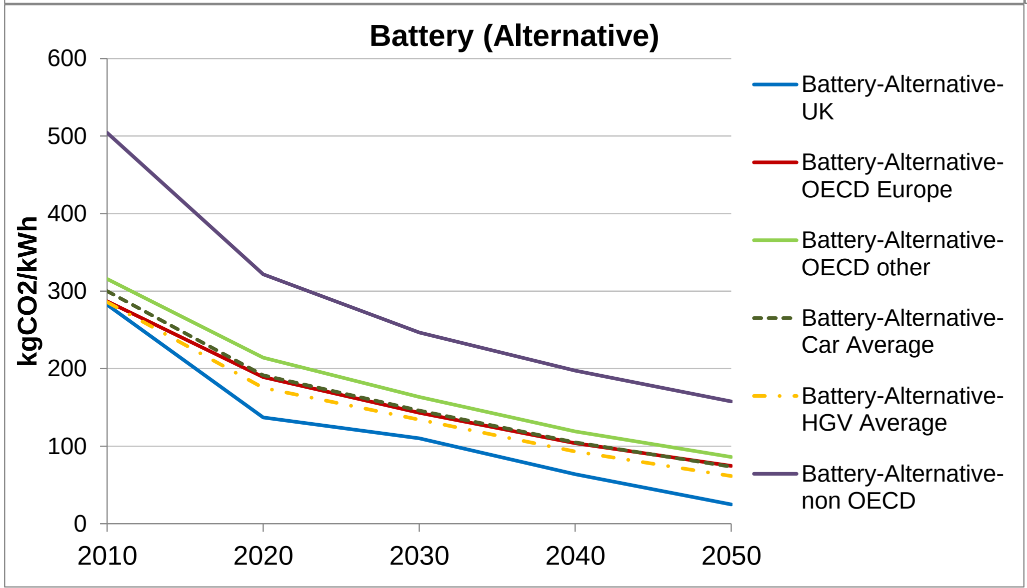




Additional modelling assumptions for transport:
Energy and Materials GHG intensity, charts 4







- Reduction in battery GHG intensity is due to a combination of increased energy density (i.e. fewer materials per kWh capacity) and reductions in the GHG intensity of both manufacturing process energy and the materials used in battery manufacturing.

Additional modelling assumptions for transport:
Baseline Technology Characteristics, part 1

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Petrol ICE Car	2010	2020	2030	2040	2050
Kerb weight (kg)	1,407	1,403	1,369	1,286	1,173
Lifetime (years)	14	14	14	14	14
Annual mileage (km)	13,000	13,000	13,000	13,000	13,000
% miles electric	0%	0%	0%	0%	0%
Vehicle efficiency (MJ/km, real world) - electric	0.00	0.00	0.00	0.00	0.00
Vehicle efficiency (MJ/km, real world) - non-electric	2.77	2.07	1.69	1.51	1.38
Fuel cell size (kW)	0	0	0	0	0
Fuel tank capacity (kWh)	0	0	0	0	0
Battery type	0	0	0	0	0
Battery pack size (kWh)	0.00	0.00	0.00	0.00	0.00
Battery pack weight (kg)	0	0	0	0	0

Petrol PHEV Car	2010	2020	2030	2040	2050
Kerb weight (kg)	1,532	1,471	1,419	1,327	1,206
Lifetime (years)	14	14	14	14	14
Annual mileage (km)	13,000	13,000	13,000	13,000	13,000
% miles electric	31%	43%	43%	43%	43%
Vehicle efficiency (MJ/km, real world) - electric	0.69	0.63	0.58	0.55	0.52
Vehicle efficiency (MJ/km, real world) - non-electric	2.12	1.74	1.55	1.44	1.36
Fuel cell size (kW)	0	0	0	0	0
Fuel tank capacity (kWh)	0	0	0	0	0
Battery type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery pack size (kWh)	8.26	7.48	6.00	5.37	4.80
Battery pack weight (kg)	121	65	47	38	31

Additional modelling assumptions for transport:
Baseline Technology Characteristics, part 2

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Petrol REEV Car	2010	2020	2030	2040	2050
Kerb weight (kg)	1,592	1,474	1,406	1,309	1,186
Lifetime (years)	14	14	14	14	14
Annual mileage (km)	13,000	13,000	13,000	13,000	13,000
% miles electric	62%	62%	62%	62%	62%
Vehicle efficiency (MJ/km, real world) - electric	0.69	0.63	0.58	0.55	0.52
Vehicle efficiency (MJ/km, real world) - non-electric	2.12	1.74	1.55	1.44	1.36
Fuel cell size (kW)	0	0	0	0	0
Fuel tank capacity (kWh)	0	0	0	0	0
Battery type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery pack size (kWh)	16.52	14.96	12.01	10.75	9.60
Battery pack weight (kg)	243	220	177	158	141

BEV Car	2010	2020	2030	2040	2050
Kerb weight (kg)	1,561	1,429	1,369	1,286	1,173
Lifetime (years)	14	14	14	14	14
Annual mileage (km)	13,000	13,000	13,000	13,000	13,000
% miles electric	100%	100%	100%	100%	100%
Vehicle efficiency (MJ/km, real world) - electric	0.69	0.63	0.58	0.55	0.52
Vehicle efficiency (MJ/km, real world) - non-electric	0.00	0.00	0.00	0.00	0.00
Fuel cell size (kW)	0	0	0	0	0
Fuel tank capacity (kWh)	0	0	0	0	0
Battery type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery pack size (kWh)	44.06	49.88	48.04	50.15	51.18
Battery pack weight (kg)	464	335	262	223	185

Additional modelling assumptions for transport:
Baseline Technology Characteristics, part 3

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Diesel ICE articulated HGV	2010	2020	2030	2040	2050
Kerb weight (kg)	13,960	13,904	13,541	13,122	12,564
Lifetime (years)	8	8	8	8	8
Annual mileage (km)	119,000	119,000	119,000	119,000	119,000
% miles electric	0%	0%	0%	0%	0%
Vehicle efficiency (MJ/km, real world) - electric	0.00	0.00	0.00	0.00	0.00
Vehicle efficiency (MJ/km, real world) - non-electric	13.99	11.82	9.41	8.51	7.91
Fuel cell size (kW)	0	0	0	0	0
Fuel tank capacity (kWh)	0	0	0	0	0
Battery type	0	0	0	0	0
Battery pack size (kWh)	0.00	0.00	0.00	0.00	0.00
Battery pack weight (kg)	0	0	0	0	0

H2 FCEV articulated HGV	2010	2020	2030	2040	2050
Kerb weight (kg)	14,864	14,497	13,964	13,437	12,799
Lifetime (years)	8	8	8	8	8
Annual mileage (km)	119,000	119,000	119,000	119,000	119,000
% miles electric	0%	0%	0%	0%	0%
Vehicle efficiency (MJ/km, real world) - electric	0.00	0.00	0.00	0.00	0.00
Vehicle efficiency (MJ/km, real world) - non-electric	6.64	5.62	4.70	4.18	3.77
Fuel cell size (kW)	317	334	351	351	351
Fuel tank capacity (kWh)	1845	1562	1306	1162	1047
Battery type	Li-ion	Li-ion	Li-ion	Li-ion	Li-ion
Battery pack size (kWh)	5.27	4.46	3.27	2.73	2.33
Battery pack weight (kg)	78	38	26	19	15

