Chapter Two

Concepts and Applications of Life Cycle Assessment

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA), in the present context, is an environmental management tool used to understand and compare how a product or service is provided 'from cradle to grave'[1], Forbes *et al* (2001). The technique examines every stage of a product's life cycle, from raw materials acquisition, through manufacture, distribution, use, reuse/recycling and final disposal. In addition, every operation or unit process within a stage is included. The inputs (energy consumption and material resources) and outputs (emissions and cost) are calculated. The inputs and outputs are aggregated over the life cycle. The environmental issues associated with these inputs and outputs are then evaluated. It should be noted that the LCAs were preceded by Life Cycle Costing studies, but these tended to omit environmental factors from the costing process.

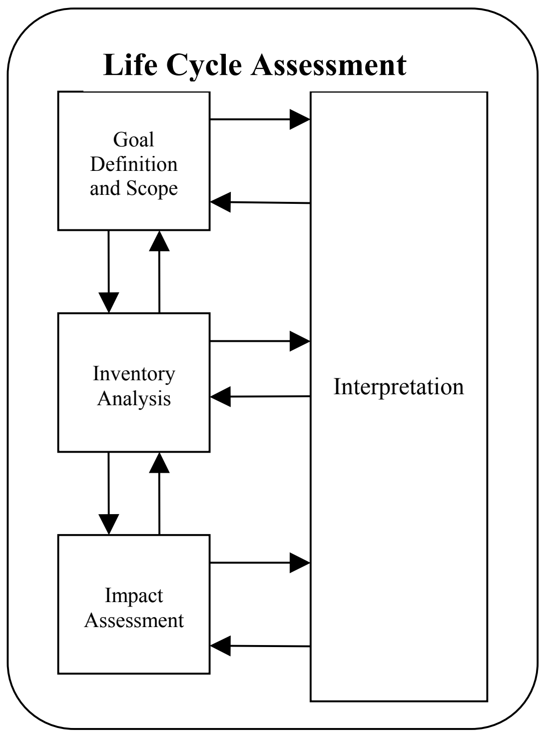
A typical LCA consists of four stages: Goal Definition and Scope, Inventory Analysis, Life Cycle Impact Assessment and Interpretation, as defined by the International Standardisation Organisation (ISO14040): 1997 Environmental Management – Life Cycle Assessment – Principles and Framework. Figure 2.1 illustrates each stage of a typical LCA and the linkage between them. Simplified and complex LCAs exist specific to particular applications, all of which follow the same basic procedure. Nicolay (2000)

[1] *Cradle-to-grave* is a term used to describe the life cycle of a product from its first derivatives to its end-use. e.g. Oil derived from an oil field, refined into petrol and used within a vehicle.

produced a simplified LCA for the automotive sector comparing diesel, petrol and electric vehicles.

Further details on LCA studies can be found within DETR (2002), Rosselot and Allen (2002), Sheenan *et al* (1998).

Figure 2.1 Life Cycle Assessment Framework



Source: Forbes *et al* (2001)

A LCA differs from other environmental management tools as integration over time is considered together with the stages a product will pass through over its lifetime, ETSU (2000). By adopting a holistic approach, LCAs avoid the problem of changing environmental impacts. This is to say that any positive and negative impacts through a products life system are combined to produce a net impact; the significance of which becomes apparent when comparing various vehicle and fuel combinations.

2.2 Goal and Scope Definition

> *The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study and the intended audience – ISO 14041*

The goal of this LCA is to compare and contrast the relative feasibility of compressed landfill gas (CLG) against competitor fuels[2] within public service vehicles (PSVs)[3].

The scope of the LCA defines the system boundaries. In theory a full LCA would include all upstream and downstream processes associated with the production and use of the vehicles and vehicle fuels. For the purpose of this LCA, the vehicle fuels and vehicles are compared on a full LCA, "cradle-to-grave" basis.

It becomes clear to see that two separate cycles exist, see Figure 2.2:

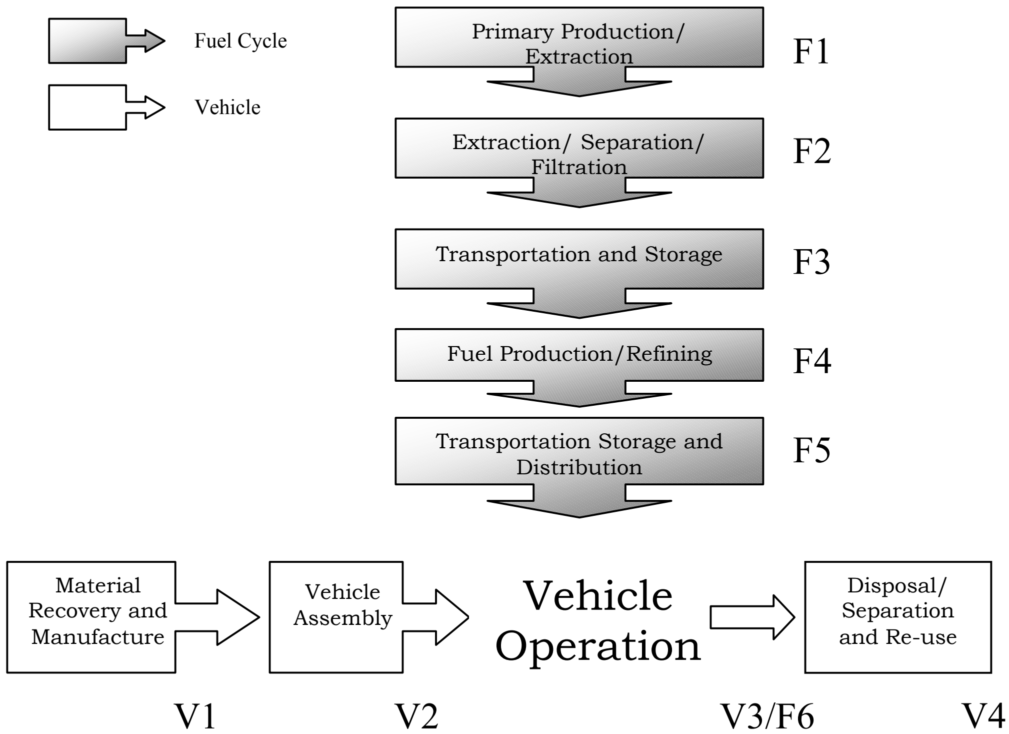
- Fuel Cycle
- Vehicle Cycle

The cycles are linked and define the system boundaries, together with the stages to be used within the Inventory Analysis, see Figure 2.1.

[2] Competitor fuels include: Petrol, Diesel, Ultra-Low Sulphur Petrol (ULSP), Ultra-Low Sulphur Diesel (ULSD), Liquefied Petroleum Gas (LPG), Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG) and Electric.

[3] Public Service Vehicles include: Buses, Heavy Goods Vehicles (HGVs) and Small Vans.

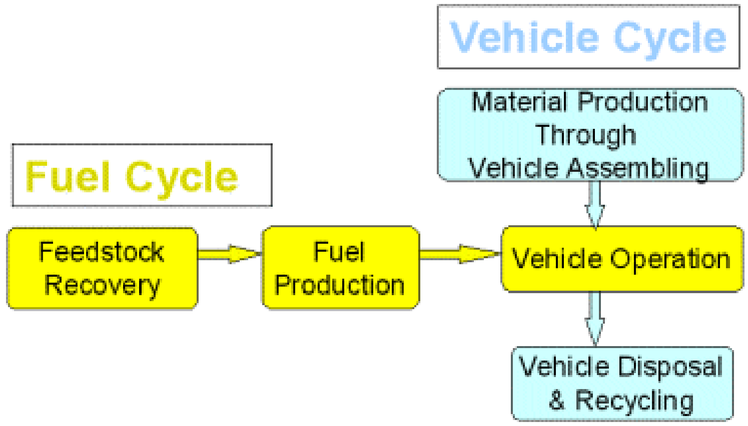
Figure 2.2 LCA Fuel and Vehicle Cycle



The fuel cycle consists of six stages (F1-F6) and the vehicle cycle contains four stages (V1-V4). Both cycles can be used descriptively to document each stage within the life cycle of any fuel and vehicle combination. This includes the life cycle of traditional and alternative fuels. Within each stage the emissions are under examination. At any given stage (e.g. F4), a detailed analysis is available, together with a breakdown of the percentage contribution the stage makes to the overall LCA.

Other LCA studies have produced fuel and vehicle cycles. Premier amongst them being the GREET Model 1.5a, Wang (1999) (see Fig. 2.3)

Figure 2.3 LCA GREET Model 1.5a



Source: Wang, M (1999)

To-date the GREET model is the most widely used LCA, from a transport view, in America, with a European version of the GREET model under preparation. Other LCA studies world-wide use the model as a template for their own work, see Deluchi (1993), EA (2001), Gaines *et al* (1998), General Motors Corporation (2001), Hackney and Neufville (2001), Wang and Huang (1999) and Winebrake *et al* (2000).

2.3 Inventory Analysis

Inventory Analysis gathers data on the environmental burdens associated with the product. An inventory is simply a listing of how much energy or material is used during the life cycles and how much waste is generated. In order to draw comparisons and allow interpretation, LCA relates each environmental burden to the same functional unit, e.g. per giga-joule (GJ) of final product, where this is a fuel or energy source.

2.4 Impact Assessment

With many LCAs a conclusion can be reached on completion of the Inventory Analysis. However, more complex LCAs do not have this luxury and it becomes necessary to assess the environmental burdens. Typically, the burdens are grouped, termed **classification**, and estimations are made of their individual contribution to that particular environmental impact. This process is referred to as **characterisation**. It allows the most significant burden to be identified. The burdens of concern within the present study are the environmental impacts of Global Warming Potential (GWP) and Human Toxicity (HT) and in particular their impact on public health, see Chapter 6.

For this LCA, emissions classification occurs by assessing global and local air quality: (1) Greenhouse Gas (GHG) emissions, which contribute to GWP and (2) Local Air Quality (LAQ) emissions, which contribute to HT. The emissions from each stage are summed over their life cycle followed by an identification of the major and minor contributors to the overall emission output.

Energy classification is based upon the total energy use throughout the life cycle and characterisation occurs as above.

2.5 Interpretation

Throughout an LCA, it is necessary to revise the scope of the study by considering the results emerging from the inventory analysis and impact assessment. Interpretation is used to identify gaps in the data, redirect stages and modify initial goals and system boundaries.

Prioritisation is needed to assess the environmental impacts and to decide upon the most important category on which to base the assessment.

2.6 Assessment Criteria

On completion of the building blocks that make up an LCA, the criterion for each vehicle and fuel cycle stage is summed to provide an overall value for further assessment. Taking the example of the criterion emission, an overall life cycle emission in the vehicle stage for producing and operating a diesel powered car may be different than the emission as a result of producing and operating a petrol powered car. The following formula is derived to calculate life cycle emissions

$$E = \sum_{i=1}^{6} Fi + \sum_{i=1}^{4} Vi \tag{2.1}$$

where,

E - Overall emission (g)

F - Fuel cycle emission (g) (stages F1-F6)

V - Vehicle cycle emission (g) (stages V1-V4).

This equation can be modified by replacing the variable E (emissions) with either, EC (energy consumption) or MR (material resources).

2.7 Emissions

The emissions from each stage are either calculated or collected from various literature sources. For example, The Digest of UK Energy Statistics (DUKES) is produced annually by the Department of Trade and Industry (DTI) and provides information given to the DTI (1997, 1998) from manufacturing industry. All oil and gas usage within the UK is documented within, together with energy consumption levels, electricity supply and demand, import and export of oil and gas, combined heat and power and other solid fuel industries. With a prior knowledge of the mass inputs and outputs of fuels, emissions from each stage within the fuel cycle can be estimated.

2.8 Energy Consumption

Crude oil is imported and domestically produced within oil fields in the North Sea. It is then transported to shore, refined to produce a transport fuel, transported to a filling station and used within a vehicle. It then becomes possible to estimate the amount of energy consumed during each stage of the life cycle. Each process within the cycle consumes energy that is lost in heat and in transformation. With a knowledge of extraction, transportation, refining and storage efficiencies, estimations of what can be made throughout the life cycle. These estimates are used on a comparative basis and are good estimates of the overall efficiencies of various fuel and vehicle combinations.

2.9 Material Resources

The materials used to construct a vehicle have major financial and environmental impacts. On comparison of various vehicle types using the same vehicle fuel, slight modifications can result in some benefits. An example of which are tyres, the larger the surface area in contact with the road, the higher the energy requirement that is needed to propel the vehicle. The National Energy Conservation Centre (NECC) provides information to assist drivers and highlight the benefits of using energy saving driving techniques.

Comparing the material resources used to manufacture vehicle and fuels can affect the overall life cycle.

2.10 Choice of Criterion

Emissions, Energy Consumption and Material Resources can all be used to compare and contrast alternative fuels on a LCA basis. However the emissions criterion has the largest impact on public health, of the three under examination, on a local and global scale. The direct and indirect emissions released as a result of the use of public service vehicles is of great interest to government agencies, local authorities and the public. It is for these reasons that the study focuses solely upon emissions. Moreover, the combination of the three criteria in a much larger LCA is beyond the time scale of the researcher.

2.11 Choice of Fuels

In the assessment of conventional (petrol and diesel) and alternative fuels, nine fuel cycles are considered which represent the range of commercially available fuels in the UK in the year 2000.

Some fuels are derived from petroleum based fuels and others from Natural Gas (NG) and Landfill Gas (LFG), see Figure 2.4.

Figure 2.4 – Fuel Cycles

(1) Petrol (2) Diesel (3) LPG	Petroleum Based Fuels
(4) NG to CNG (5) NG to LNG	Natural Gas Based Fuels
(6) Electric (7) Green Electric	Electric Based Fuels
(8) LFG to CNG (9) LFG to LNG	Landfill Gas Based Fuels

2.12 Summary

On completion of the LCA a comparison, on a purely environmental basis, can be made for each conventional and alternative fuel. The global and local impact each fuel has on the environment can then be assessed in the calculation of GWP and HT. A sensitivity analysis can then be used to simulate change in the system and highlight the most significant contributors to the life cycle emissions profiles of each fuel.

Figure 2.2 forms the inventory analysis block of Figure 2.1, from which the impact assessment, through the calculation of GWP and HT, can be made. The uncertainty and sensitivity analysis sections then form the backbone of the interpretation section in Figure 2.1. The overall goal and scope have been defined in this chapter.