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Combined life cycle and economic assessment of wood based bio fuels in Norway

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Problem Description

Main production routes for bio-fuel production from woody biomass. Literature survey of life cycle assessment and cost estimates of wood based bio-fuel production. Survey main elements of life cycle assessment and investment analysis theory. Development of a combined investment and hybrid life cycle analysis framework and compile a case study on bio-fuel production in Norway.

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Wisdom is a lot like manure. It works the best when it is spread around.
– unknown

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Preface

In the eventful year of 1776, Adam Smith observed in *An Inquiry into the Nature and Causes of the Wealth of Nations* that men act in their self-interest. Unlike selfishness, self-interest does contain a dimension of sympathy, indeed Adam Smith believed that moral sentiments and self-interest would eventually add up. Thus, within a sense, it is in our self-interest to care for the environment.

This idea existed in my mind for a while; If Adam Smith's observations are true, then environmental systems analysis cannot exist without economic considerations. The motivation for this pre-thesis report is to explore that very nature. Can we make decisions that are in our economic self interest and simultaneously in the interest of the environment? Can modern economic theory coupled with environmental assessment provide a framework in which we are able to explore this frontier?

I approached my academic supervisor, associate professor Anders Hammer Strømman at the Norwegian University of Science and Technology (NTNU) on this matter. One of the challenges has been finding a suitable case, where such a framework can be applied. Luckily, Ryan Bright, also a student writing his thesis at the same time had made an extensive study on bio-ethanol production from Norwegian wood mass.

The methods and models devised for this thesis are crude, but they do provide some sort of a basis on which someone might bother to make something great. The mere mention of combining environmental and economic assessment creates awe among many and should inspire others.

Michal Gryczon

Abstract

The increasing global demand for energy coupled with decreasing oil-supplies, and increasing risk of adverse climate change due to anthropogenic carbon emissions has created the need for combined economic and environmental assessment.

This thesis attempt at devising such a framework based upon Life Cycle Assessment (LCA) and Life Cycle Costing (LCC). These methodologies represent two well established approaches for measuring environmental and economic performance of industrial projects and products.

The LCA framework permits introduction of system expansion by interfacing with the greater economy by the hybrid-LCA. This approach also permits the assessment of life-cycle costs within the mathematical structure. The fundamental computations of LCA and LCC are introduced in this text in order to establish the combined assessment framework.

This assessment method is applied to two National Renewable Energy Laboratory's studies on bio-ethanol production from lignocellulose. The studies are adapted to Norwegian economic conditions in order to assess the price and emissions of ethanol production from Norwegian wood mass. By combining these performance characteristics, a mitigation price of substituting gasoline with ethanol is established for various plant sizes as well as prices of gasoline.

Sammendrag

Økende verdensbehov for energi sammen med synkende oljereserver og økende risiko for ugunstig klimaforandringer har skapt behov for kombinert økonomisk og miljømessig analyse.

Denne master-oppgaven er et forsøk på å bygge et rammeverk basert på livssyklusanalyse (LCA) og livslange kostnader (LCC). Disse metodene representerer to veletablerte tilnærminger til å måle miljømessig og økonomisk ytelse av industrielle prosjekt og produkt.

LCA rammeverket tillater systemutvidelser som omfatter regionale økonomiske strukturer ved hjelp av hybrid-LCA. Denne tilnærmingen tillater i tillegg analyse av livslange kostnader innen den matematiske struktur. Dermed er fundamentale beregninger av LCA og LCC introdusert i denne teksten, med en kombinert analyse som mål.

Metoden er brukt på to studier foretatt av National Renewable Energy Laboratory i USA, om produksjonen av biodrivstoff fra cellulose. Studiene er tilpasset norske forhold, slik at kostnader og miljøutslipp er gjort relevante. Ved å kombinere disse karakteristika, er det mulig å etablere en miljøskadebegrensningskostnad ved å erstatte bensin med etanol for en serie med prosjektstørrelser.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

For most modern economies, cheap and accessible energy has been of primary importance. Since the industrial revolution in the late 18th century, it has contributed to rapid technical advancement and modern economic affluence. Yet recently in the industrialized world there has been an increasing anxiety expressed with regards to not only global climate change (due to increasing carbon dioxide emissions), but also to the current and future energy prices and their volatility. The question of energy security has become central in modern international discourse.

Energy security implies the steady supply of energy at predictable prices, primarily fossil fuels. Access to these energy sources is often considered necessary to maintain the current global economic development. Yet price volatility due to increasing demands from emerging markets (such as China and India), social unrest in oil producing countries (among Nigeria and Iraq) and the prospect of dwindling reserves has made many developed nations worried about future energy availability. Which is why both the United States of America and the European Union have increasingly stressed the need for initiatives in expanding the use of renewable energy resources.

One of the primary energy resources discussed are bio fuels. The term bio fuel can apply for any solid, liquid and gaseous fuel that consist of, or derives from biomass. Biomass can be of any biological source, excluding biomass from geological formations (i.e. fossil fuels). As fossil fuels require millions of years before they can be used as fuel, while modern bio fuels come from resources that require less than 100 years to regenerate. In this sense, bio fuels are renewable. Bio fuels, by these standards, are considered to be a possible solution to both energy security and even possibly global climate change due to these properties (FAO 2004).

In 2004 the transportation-sector in Europe amounted to 18 per cent of all CO_2-emissions, while in Norway this figure is closer to 27 per cent [1] . The transportation sector represents a significant fraction of total emissions in the western part of the world. The European Union has recently been encouraging increased use of bio fuels within the transportation sector by implementing Directive 2003/30/EC of the European Parliament and of the Council (2003). This is also considered crucial for Europe's energy security as nearly all of the energy required by transportation comes from fossil fuels.

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[1] according to EuroStat, `http://epp.eurostat.ec.europa.eu/tgm/table.do?language=en&pcode=tsdcc210`

1.1 Bio fuels

The term bio fuels can refer to fuels for direct combustion in energy utility, such as heat or electricity, but is generally used for liquid fuels for transportation. Ethanol fuel, commonly referred to as bio-ethanol, is of primary consideration. Ethanol fuel is considered the most viable alternative to gasoline, and has been used extensively in cars in Brazil since it's introduction in the late 1970's.

Nearly all fuel ethanol produced today is either by fermentation of corn glucose in the United States or sucrose in Brazil. The European Union is third of rank among bio fuel producers world wide (MacDonald et al. 2001, Rosillo-Calle & Cortez 1998). Within the European Union, Germany is the largest, and France the second largest producer of bio fuels (van Thuijl et al. 2003). Most bio fuels in commercial production in Europe today are based on sugar beet, wheat and rapeseed, which are converted to bio-ethanol and bio-diesel. Currently it is added to regular vehicle fuel as an additive, up to 10% in some parts of the United States.

Fuel-mixtures are designated with E, for Ethanol and B, for bio-diesel, e.g. E85 consists of 85% ethanol and 15% gasoline, while E15 will consist of 15% ethanol and 85% gasoline. For bio-diesel, B100 is 100% "neat" bio-diesel, while 20% bio-diesel is designated as B20. Whenever a bio fuel product is 100%, it is considered to be "neat".

There are several production paths for bio fuel production that utilize various kinds of biomass. The most common kind of bio fuel production is from high sugars, starch, and vegetable oils commonly referred to as first generation bio fuels. Second generation bio fuels are from biomass with more complex structures, such as lignocellulosic and bio-waste materials. Second generation bio fuels have the benefit of not being possible sources of food for humans, diminishing the risk of greater volatility in prices on staple foods for human consumption.

Among all of the main types of materials used for bio fuel production, cellulose represents the most abundant source of biomass that remains largely unutilized. The global production of plant biomass, of which 90 per cent is lignocellulose, amounts to approximately 200×10^9 tonnes per year, of which $8 - 20 \times 10^9$ is accessible. The availability of bio fuels from local biomass makes production of bio fuels feasible with reasonable capital investments in many regions, with possible socio-economic benefits such as rural employment (Lynd 1996).

1.2 Bio fuels in Norway

Norwegian consumption of bio-ethanol as transport fuel is currently considered to be nigh non-existent, while bio-diesel consumption is approximately 3 per cent of total consumption by volume (Brunvoll et al. 2008). The Stoltenberg's 2nd Government $(2005 - 2009)$ aims to require 7 per cent of all road traffic fuels to be bio fuels by volume by the year 2010. The EU expects to reach a average of 4.2 per cent by the same year (Ministry of the Environment 2007).

The Norwegian Government is also concerned about possible disruptions in food availability and environmental consequences in bio fuel-exporting countries and wishes to apply a life cycle perspective on bio fuel production. To achieve this the Norwegian government is co-operating with the European Union, international NGOs, and the transport fuel industry in establishing a mechanism for promoting sustainable bio fuel production.

Bio fuels from lignocellulose (L. *lignum*; wood) presents itself as a viable source of

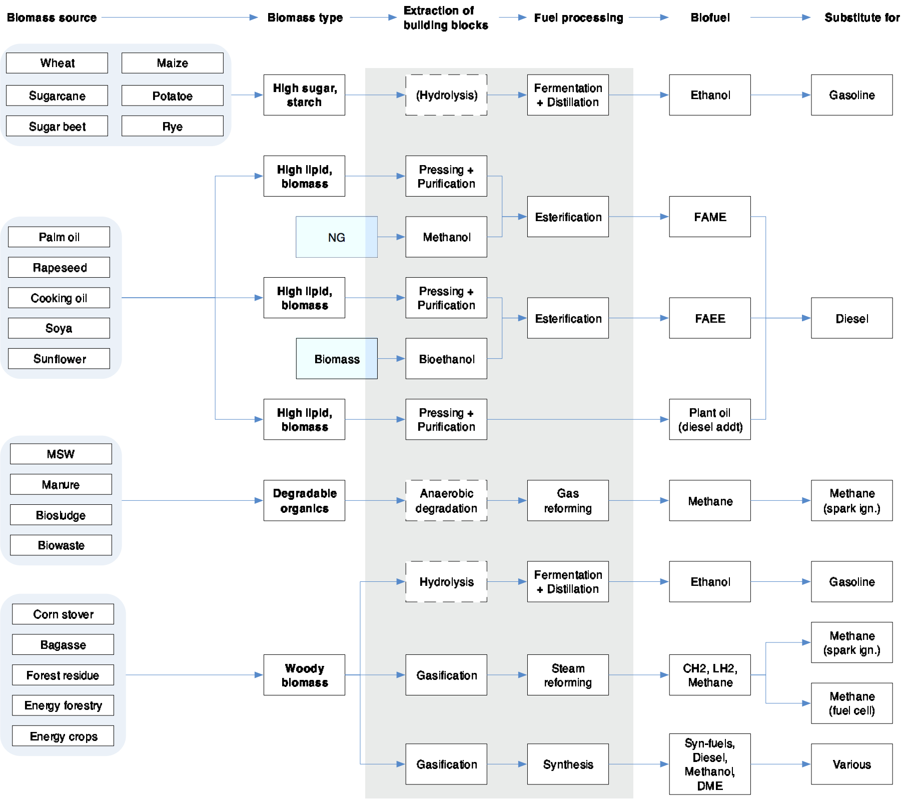

Figure 1.1: Paths for bio fuel production (Hanssen et al. n.d.)

biomass for conversion into bio fuels. Especially as lignocellulosic bio fuel production are exclusively energy crops and are not considered possible food sources. Unfortunately, all crops, for bio fuel production or otherwise, require access to water and might have to compete for this resource (Berndes et al. 2001).

Forests are an abundant resource in Norway, the climate is favourable, and the risk of food disruption could be therefore considered minor for bio fuel production from wood-mass i Norway. The abundance of wood mass that can be utilized for bio fuel production is by all means limited. Yet, the stock of wood mass has been increasing by 1.3% each year for the last 40 years[2]. The total available biomass for bio fuel production in 2006 was approximately 2 803 481 m^2 (Bright 2007). 150 969 km^2 of Norway's 385 155 km^2 land area consists of forests (Larsson & Hylen 2007). The increasing amount of available wood mass represents a resource that could potentially be applied in achieving Norway's future bio fuel goals. It could also spur a new bio fuel industry in Norway as it's oil reserves are expected to decline (NPD 2007, p. 15).

A prototype facility is being currently set up in Hønefoss, in affiliation with Norske Skog Group's Follum facility. The prototype will require 160 000 m^3 of wood mass, while the full-scale facility will require $1 - 1.5$million m^3 of wood mass and produce 65 000 tonnes of bio-diesel. This is equivalent to 4−6 per cent of all diesel consumption

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[2] according to Statistics Norway `http://www.ssb.no/english/subjects/10/04/20/skog_en/`

in the Norwegian transportation sector.

This could be a boon for the Norwegian forestry sector, which has been a significant part of the Norwegian economy for several centuries. Today it is an industry with a total revenue of 42.1 billion Norwegian kroner (NOK), which represents 5.5 per cent of all industrial revenue and 0.75 per cent of the Norwegian Gross Domestic Product. In comparison, Norwegian oil production and off-shore activity is 27 per cent of GDP.

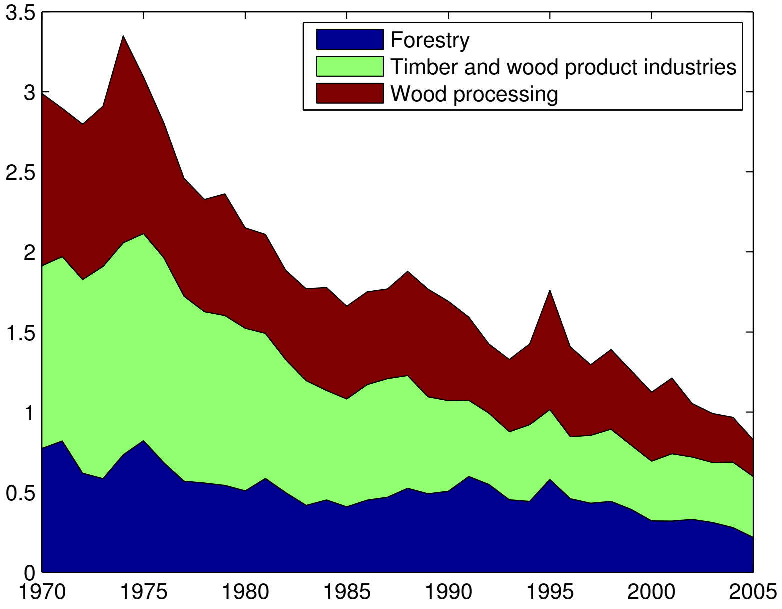

Figure 1.2: Forest industry as per cent of GDP

1.3 Report Structure

One central aim in this thesis is establishing a framework for combined economic and environmental assessment. The motivation of establishing such a framework, is to a greater degree analyse potential projects with regards to economic and environmental performance.

To fully understand the aspect of a combined economic and environmental assessment, the fundamentals of each approach has to be reviewed separately. For both the environmental and economic assessment, the concepts and structures are explored thoroughly. The aim is to use these fundamental aspects to build a unique approach that reconciles both.

A case is explored to test this framework as a proof of concept. This thesis looks at the life cycle and economic assessment of two bio fuel production methods based on studies conducted at the US National Renewable Energy Laboratory (NREL) by Wooley et al. (1999) and Phillips et al. (2007) in a Norwegian setting. By expanding the studies' data and factoring economies of scale, and extensive model has been produced. The economic and environmental performance is assessed as a function of the facilities size and is compared to the economic and environmental performance of the product it is replacing, gasoline production.

Chapter 2

Basic Structures of Environmental and Economic Assessment

This framework consists of an environmental and economic assessment. Starting at their respective fundamentals, the aim is to build a common framework in which by both economic and environmental performance can be measured. The framework consists of a hybrid approach consisting of Life Cycle Assessment and Input-Output Analysis (IOA) as an environmental foundation, while Discounted Cash-Flows (DCFs) and Cost Accounting provide the economic analytical content. The aim is to provide a unified tool-set that can be applied to studies that require both an environmental and economic assessment from a life-cycle perspective.

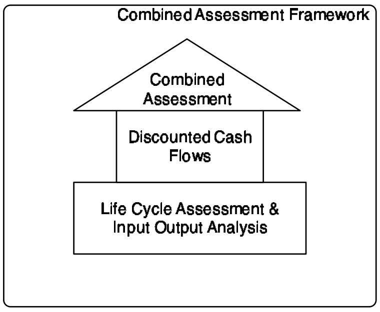

Figure 2.1: The model buildup

2.1 Environmental Assessment

It has become increasingly important for companies and public actors to assess human interaction with the environment for various reasons. Through the International Organization for Standardization (ISO), it has been established that in order to achieve sound environmental performance, it is required that an organization has a systematic approach to continuous improvement through an environmental management system (EMS).

Among such systems within the ISO 14000 family of standards is Life Cycle Assessment. LCA is primarily applied for identifying problems and opportunities for the *environmental performance* of products. It is supposed to give industries, governments and non-governmental organizations the opportunity to plan, prioritize and design products and processes that reduce resource use and environmental impact. These impacts can be aggregated into several distinct impact categories, such as global warming potential (greenhouse gases), ozone layer depletion, human toxicity, aquatic or terrestrial eco-toxicity, acidification, and others. LCA is just one of several environmental management techniques[1]. It might not always be the most suited approach for all situations, such as economic and social aspects of a product (ISO 2006). Some of these limitations will be addressed, specifically economic aspects, as the *computational* framework for LCA might provide possibilities in this regard (see section 2.5).

2.1.1 International Standards

The ISO standardization encourages a common set of principles and framework (figure 2.2). It does not describe the LCA technique in detail, nor specify methodologies for each phase of a LCA study. But it is a comprehensive and systematic guide to establishing procedures for quantifying and evaluating environmental impacts. Areas in which LCA can be applied, according to ISO 14040, are among other:

- Improve environmental performance of products at various points in their life cycle
- Strategic purposes, priority setting, etc.
- Selecting proper environmental indicators of environmental performance
- Marketing, eco-labelling schemes, environmental declarations

Interpretation

The framework allows continuous revision of all aspects within the LCA-study. As the goal and scope, inventory analysis, and impact assessment, are established, they are continuously reiterated within the context of how they are interpreted. The findings need to be considered within the goal and scope, which is the initial step. The findings extrapolated from the interpretation may take the form of conclusions and recommendations with regards to the environmental performance.

Goal and scope

Within the *goal and scope* phase the data is quantified and performance characteristics are established in such a manner that allows comparability between LCA results, i.e. ensure that comparisons are done on a common basis. There is also a need to establish the product systems as models and establish the *system boundary* of processes included

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[1] other methods are among other risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment

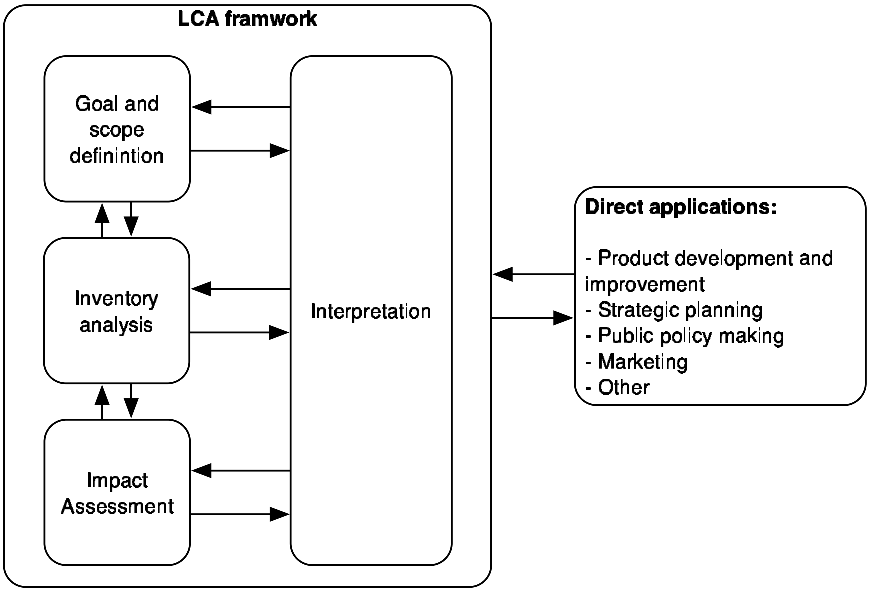

Figure 2.2: The ISO 14040 Life Cycle Assessment Framework

in the study. These processes might include acquisition of raw materials, main manufacturing, distribution, energy (fuels), use and maintenance, disposal and wastes, and any other additional operations required to realize the product being studied.

Within the goal and scope, the establishment of a functional unit is used to allow comparability of different *quantities* and *methods* of satisfying a specific demand. The functional unit is established as a measurable property of a product. It is something that the consumer of the product can demand. This can be requirements that fulfills a specific need or a quantifiable performance unit. This unit can be physical amounts, mass, volume, energy or any other combination of measurable unit demand[2].

Inventory Analysis

Data collection and calculation within the system boundary that has been established is referred to as the inventory. As data is collected and identified the system is established. This may require revisions to the goal and scope, as new knowledge and information is acquired. There are obviously limits to the size of the inventory. ISO 14041 states: "*Ideally, the system should be modelled [sic] in such a manner that inputs and outputs at its boundaries are elementary flows*" (ISO 2006). This implies that all processes directly and indirectly linked to the product should be included in the study.

One can imagine that including all of the processes required for a certain product will ultimately become complex, prohibitively expensive, and practically impossible. Such limitations of data collection require setting proper system boundaries of a LCA-study. One solution for reducing data collection efforts is to expand the data with generic Life Cycle Inventory (LCI) databases, such as the EcoInvent-database.

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[2] examples can be heat delivered per floor area (kW/m^2) or services such as distances travelled (person × km)

It has also been proposed to combine the traditional process based LCA with Input-Output Analysis. This *hybrid* approach can be used to build more complete inventory results, as it recovers process flows that are *cut off* when identifying such flows. Databases used for these approach are e.g. the Missing Inventory Estimation Tool (MIET) or by manually applying Symmetric Input-Output Tables (SIOT) to the process flows (see section 2.2.6).

Impact Assessment

Life cycle impact assessment (LCIA) is aimed at evaluating the significance of possible environmental impacts established by the inventory data. Impacts are categorized in such a manner that their consequences and scope can be understood. The evaluation and "weighing" of impacts can introduce *subjectivity* to the study. ISO 14040 guidelines encourages high level of transparency when conducting the impact assessment of a study. This would allow third parties to understand *how* impacts were evaluated. Similar studies may vary in results, thus the importance of LCIA.

2.2 Computational structure

The basis for modern LCA computation is Wassily Wassilyovitch Leontief's seminal work on a System of National Accounts which resulted in Input-Output Analysis (Leontief 1936). The premise of IOA is the self-enclosed nation and the transactions that occur during a single year. Similarly, for LCA the premise is an enclosed system defined by its *system boundary*. The system boundary is established during the goal and scope of its study (see 2.1.1).

Since computation of both LCA and IOA so similar, it provides the possibility of introducing a *hybrid* structure called a hybrid-LCA (see section 2.2.6). The differences between IOA and LCA is that the former is concerned with monetary flows between industries, while the latter is concerned with physical flows between specific industrial processes.

To meet a certain demand, the producers themselves[3] need to create additional *intermediate demand* for goods they will require as input to their own production. This creates a *causally connected network* of producers, where all intermediate demand can be mutually dependent. With this, the total output required is dependent on the intermediate and final demand can be expressed (2.1).

$$\text{intermediate demand} + \text{final demand} = \text{amount produced} \tag{2.1}$$

2.2.1 Intermediate Demand

For a list of processes that occur within an observable system, these processes must be causally connected. For instance, the process of baking bread will require an oven, that requires electricity and in turn needs to be generated at a power plant. These processes will intersect at various points, e.g. workers at the power plant will need some of the bread, or factories require electricity to manufacture ovens. The processes' interdependence is crucial for establishing these computations. The observed process flows can then be arranged in an array (figure 2.3).

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[3] either industry-sectors within a nation (IOA), or specific production processes in manufacturing a good (LCA)

Process 1 to 1	Process 1 to 2	Process 1 to 3
Process 2 to 1	Process 2 to 2	Process 2 to 3
Process 3 to 1	Process 3 to 2	Process 3 to 3

Figure 2.3: Array structure of intermediate demand between 3 processes

This corresponds to *inventory analysis*, where data is collected and structured in a certain way. For LCA and IOA, as the scope of the data collection grows, so will the structured size of the data-array. A study can consist of anywhere between three and several hundred (or even thousands) of individual product and process compartments. Some of the data is collected directly from the analysis of certain processes and their interdependence, while others are to a greater degree reliant on generic databases on products and their relationships to others. The data-collection will eventually resemble something of a "recipe" of requirements. Indeed, by reading figure 2.3 it is possible to see that the first column represents all the requirements from processes 1 through 3 to process 1.

The process array is always symmetric. This means that the "recipes" for all processes that are within the scope of the system in question are taken into consideration. This encourages the use of generic processes to complete the system. For most LCA software, this is done automatically or set by specific software options.

The understanding of the mathematical structure is crucial for further development of a more advanced combined system of environmental and economic assessment. This is due to specific underlying properties of the process structure in mathematical terms, which are explained in the following sections.

2.2.2 Flows and Coefficients

In mathematical terms, consider the enclosed system[4] divided into n individual production sectors. The *production vector* of the amount produced $\mathbf{g}$ in $\mathbb{R}^n$ lists the output of each sector. The products are consumed in a non-productive sector, where they satisfy a *final demand* $\mathbf{f}$. The final demand can represent any consumer demand, be it public, government, or any other external demand. The intermediate output that is required to satisfy the final demand is expressed as an array $\mathbf{Z}$ (akin to the array in figure 2.3, where the sum of intermediate output is $\mathbf{Zi}$ (2.2).

$$\mathbf{Zi} + \mathbf{f} = \mathbf{g} \tag{2.2}$$

The structure in matrix terms can be established as follows

$$\mathbf{Z} = \begin{bmatrix} z_{ii} & \cdots & z_{in} \\ \vdots & \ddots & \vdots \\ z_{ni} & \cdots & z_{nn} \end{bmatrix}, \quad \mathbf{g} = \begin{bmatrix} g_i \\ \vdots \\ g_n \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} f_i \\ \vdots \\ g_n \end{bmatrix}, \quad \mathbf{i} = \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$

This means that sum of all intermediate use of a certain product i in processes z_{ii} all the way through z_{in} and the final consumer demand f_i is the total output of that product. This is true for all of the products that are observed within the system that is observed, also expressed as (2.3). This is how the life cycle inventory is established.

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[4] be it a nation's economy or manufacturing process

$$f_i = \sum_j z_{i,j} + g_i, \quad \forall i \tag{2.3}$$

Once the observation of flows within the system for all products is established, the system is of little use until it can be applied to calculating the total output that occurs due to certain arbitrary demand. In other words, one would like to observe total system output $\mathbf{x}$ as a function of certain demands $\mathbf{y}$ in the form $\mathbf{A}(\mathbf{y}) = \mathbf{x}$.

For the intermediate demands for products to be a function of output, a requirements coefficient a_{ij} has to be established for each intermediate process (2.4).

$$z_{ij} = a_{ij} g_j \Rightarrow a_{ij} = \frac{z_{ij}}{g_j} \tag{2.4}$$

This should be true for all intermediate processes within the system, and the coefficient matrix $\mathbf{A}$ can be established (2.5). The coefficient matrix is central for the mathematical structure of both LCA and IOA, as it is the basis for calculating the output as a function of specific demands.

$$\mathbf{A} = \begin{bmatrix} a_{ii} & \cdots & a_{in} \\ \vdots & \ddots & \vdots \\ a_{ni} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} \frac{z_{ii}}{g_i} & \cdots & \frac{z_{in}}{g_n} \\ \vdots & \ddots & \vdots \\ \frac{z_{ni}}{g_i} & \cdots & \frac{z_{nn}}{g_n} \end{bmatrix} \tag{2.5}$$

$$\mathbf{Ag} = \mathbf{Zi} \Rightarrow \mathbf{A} = \mathbf{Z\hat{g}}^{-1} \tag{2.6}$$

As the coefficient matrix (2.5) established in matrix notation is also possible (2.6). This notation can also be applied in numerical software environments, such as MATLAB or GNU Octave.

```
        >> A = g * inv(diag(Z));
```

From equations 2.2 and 2.6 it is established that the total output is the coefficients by total output and the final demand is also true (2.7).

$$\mathbf{g} = \mathbf{Ag} + \mathbf{f} \tag{2.7}$$

2.2.3 The Leontief Output Model

If $\mathbf{g}$ and $\mathbf{f}$ are the observed output and final demand, from a survey of the system that was analyzed, it is now possible to establish an arbitrary output $\mathbf{x}$ and final demand $\mathbf{y}$ (2.9). The arbitrary output and demand allows the practitioner to analyse changes in output and demand, and their effect on the entire production system. This output model can be referred to as Leontief's Output Model (2.8).

$$\mathbf{x} = \mathbf{Ax} + \mathbf{y} \tag{2.8}$$

The model can be solved algebraically as a function of final demand $\mathbf{A}(\mathbf{y}) = \mathbf{x}$ (2.9).

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y} \tag{2.9}$$

The model (2.8) can then calculate any output as a function of a demand, for either a national economy (IOA) or a production system (LCA). The model will produce the required total output to satisfy a specific demand $\mathbf{y}$.

Example

Observing the flow of goods it is observed that there are interprocess flows of goods **Z** and a final demand of those same goods **f**.

$$\mathbf{Z} = \begin{bmatrix} 50 & 20 & 20 \\ 20 & 15 & 10 \\ 10 & 5 & 30 \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} 10 \\ 5 \\ 55 \end{bmatrix}$$

The total output due to these intermediate and final demands (2.2) would be

$$\mathbf{g} = \begin{bmatrix} 50 & + & 20 & + & 20 \\ 20 & + & 15 & + & 10 \\ 10 & + & 5 & + & 30 \end{bmatrix} + \begin{bmatrix} 10 \\ 5 \\ 55 \end{bmatrix} = \begin{bmatrix} 100 \\ 50 \\ 100 \end{bmatrix}$$

From this, the coefficient matrix (2.6) can be established as

$$\mathbf{A} = \begin{bmatrix} .50 & .40 & .20 \\ .20 & .30 & .10 \\ .10 & .10 & .30 \end{bmatrix}$$

The resulting **A**-matrix can be applied to the Leontief-model (2.8) for any arbitrary final demand. If there is a final demand for only one unit of the first good, applying equation 2.9, the total output of all goods to satisfy this demand would be

$$\mathbf{x} = \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} .50 & .40 & .20 \\ .20 & .30 & .10 \\ .10 & .10 & .30 \end{bmatrix} \right)^{-1} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 2.9630 \\ 0.9259 \\ 0.5556 \end{bmatrix}$$

2.2.4 Computing Impact Assessment

Within LCA and IOA, the total output also assumed to contribute to environmental emissions. The total output of each good has a set of attributed emissions α through β within a stressor matrix **S** (2.10)

$$\mathbf{S} = \begin{bmatrix} s_{\alpha i} & \cdots & s_{\alpha n} \\ \vdots & \ddots & \vdots \\ s_{\beta i} & \cdots & s_{\beta n} \end{bmatrix} \tag{2.10}$$

The total emissions are

$$\mathbf{e} = \mathbf{S}\mathbf{x} \tag{2.11}$$

Example

In the example above, we were able to asses total unit outputs due to one specific final demand.

$$\mathbf{x} = \begin{bmatrix} 2.9630 \\ 0.9259 \\ 0.5556 \end{bmatrix}$$

The *per unit emissions* for each of the processes (table 2.2.4) represent three unique kinds of emissions coming due to each of the process outputs.

	Process 1	Process 2	Process 3
Emission 1	14	98	72
Emission 2	21	32	41
Emission 3	82	55	10

Table 2.1: Example: Emissions per unit of three processes

The emissions from these processes (table 2.2.4) results in a stressor-matrix

$$\mathbf{S} = \begin{bmatrix} 14 & 98 & 72 \\ 21 & 32 & 41 \\ 82 & 55 & 10 \end{bmatrix}$$

Thus for the given $\mathbf{x}$ the total emissions (2.11) are

$$\mathbf{e} = \begin{bmatrix} 2.9630 \\ 0.9259 \\ 0.5556 \end{bmatrix} \begin{bmatrix} 14 & 98 & 72 \\ 21 & 32 & 41 \\ 82 & 55 & 10 \end{bmatrix} = \begin{bmatrix} 172.22 \\ 114.63 \\ 299.44 \end{bmatrix}$$

The resulting emissions the vector of total emissions, each element represents the total emissions of its respective kind.

These emissions can be put into further compartments, by what is called characterization-matrices. Such matrices give an increasingly subjective “score” of environmental performance, as different environmental emissions with unique characteristics are lumped into general categories. Such characterization will ultimately be specific to each study. It can be useful when comparing the life-cycle of several different kinds of products and their relative environmental score. This thesis won’t delve deeper into characterization, yet it is worth mentioning, as in increasingly expansive studies that span numerous products and production processes might require some easily comparable environmental benchmarks.

2.2.5 The Dual Price Model

The properties of the **A**-matrix allows it not only to establish the required output per demand, but also a price model. The Leontief price-model is derived from the Leontief output-model 2.8 where the product price is equal to the inter industry price (production price) and the value-added (2.12). The price model is established by the transposed of the output model. The output model also referred to as the primal model and the price model as the dual model.

$$\mathbf{p} = \mathbf{A}^{\mathbf{T}}\mathbf{p} + \mathbf{v} \tag{2.12}$$

The price-model functions in the same manner as the output-model. With the model changes in prices due to changes in value added, such as labour costs and taxes can be observed. Solved with respect to the price vector $\mathbf{p}$ results in the equation 2.13.

$$\mathbf{p} = (\mathbf{I} - \mathbf{A}^{\mathbf{T}})^{-1}\mathbf{v} \tag{2.13}$$

The output model and the price model, expressed as equations 2.8 and 2.12, are the initial starting points for the combined assessment. This is due to the primal model dealing with outputs and the resulting emissions and the dual model used for calculating unit prices. The dual model hasn’t been discussed in literature as much as the primal, mainly as the physical outputs generated from the primal model having direct application for various kinds of analysis, especially environmental assessment.

The dual model has been used for analyzing how the technologies that produce certain outputs will affect the their respective prices, also how the costs of labour and capital in the value-added might change prices as well. These attributes of the dual model, combined with the following section, will be used to build a coherent combined model.

2.2.6 Hybrid LCA

As discussed in section 2.1.1, the hybrid approach provides the possibility of completing a inventory assessment beyond the production processes themselves. Within a hybrid-LCA, the Life Cycle Assessment of a product is set in the greater context of an economic system. The economic system usually consists of the national economy of the country where the product is being produced. Indeed, the surrounding economy is not limited to the nation-state in which the production resides. This will eventually add to complexity that is hard to manage. For most production processes, and their life-cycles, the hosting country and that countries closest trading partners.

The study of monetary flows between industrial sectors within a nation, and the flows between several nations is referred to as Input-Output Analysis. The hybrid-LCA reconciles the physical flows between processes within a LCA-study and the monetary flows between industries as a result of the processes occurring within the LCA. This distinction between the primary LCA and the supporting and secondary ioa, is generally referred to as the foreground and the background systems, respectively.

The relationship between the foreground (physical) and background (monetary) systems is reconciled in the form of purchase prices for supplying the processes necessary between the systems. This is possible both ways, as the national industries can possibly make purchases from the production system being analyzed as well as the system making purchases from the various industries.

The structure of coefficients that have been established (2.6) for both the foreground system and the background systems are designated with subscripts $_\mathbf{f}$ and $_\mathbf{b}$ respectively, this results with Leontief's Model (2.8) being partitioned into compartments (2.14)

$$\left(\begin{array}{c}\mathbf{x_f}\\ \hline \mathbf{x_b}\end{array}\right) = \left(\begin{array}{c|c}\mathbf{A_{ff}} & \mathbf{A_{fb}}\\ \hline \mathbf{A_{bf}} & \mathbf{A_{bb}}\end{array}\right)\left(\begin{array}{c}\mathbf{x_f}\\ \hline \mathbf{x_b}\end{array}\right) + \left(\begin{array}{c}\mathbf{y_f}\\ \hline \mathbf{y_b}\end{array}\right) \tag{2.14}$$

The partitioning of the model into distinct systems not only allows the system boundary to expand, but also contributions from industries as well as all of the nations included in the system. The analysis of each sub-system and their contribution for both the output-model as well as the price-model is a central element of the combined framework this thesis attempts to establish. For a two sub-system model, the partitioning can be observed without loss of context for the output-model (2.15) and the price-model (2.16).

$$\mathbf{x_f} = \mathbf{A_{ff}x_f} + \mathbf{A_{fb}x_b} + \mathbf{y_f} \tag{2.15a}$$
$$\mathbf{x_b} = \mathbf{A_{bf}x_f} + \mathbf{A_{bb}x_b} + \mathbf{y_b} \tag{2.15b}$$

$$\mathbf{p_f} = \mathbf{A_{ff}^T p_f} + \mathbf{A_{bf}^T p_b} + \mathbf{v_f} \tag{2.16a}$$
$$\mathbf{p_b} = \mathbf{A_{fb}^T p_f} + \mathbf{A_{bb}^T p_b} + \mathbf{v_b} \tag{2.16b}$$

2.3 Economic Assessment

One of the primary use of economic analysis is to assess the financial viability of a certain action, such as providing a new product or service. To measure this viability one has to look to the long term, as revenues and costs do not occur at the same point in time. Many projects might require large investments relative to future incomes, have high costs later in their life cycle, or both.

The use of economic analysis is used by both private actors (such as companies) as well as public ones (such as governments). These actors have different perspectives and aims when it comes to investments. They might also value benefits and costs at different measures. Governments tend to include third-party costs and benefits (externalities) derived from certain investments, while private investors will only consider the first-party benefits and costs. The analysis of benefits and costs in the framework in this thesis is valued in monetary terms.

2.3.1 Cash flows

The discrepancy in *monetary timing* needs to be addressed not only with regards to capital, labour, and production costs, but also how the value of money changes with time. One such method is the concept of cash flows.

Cash flows are an integral part of economic analysis and are the building blocks of investment theory. They can be observed in their quantity and timing (as illustrated 2.4). In economic analysis the cash flows are often simplified by occurring at set intervals, called periods. Each period is usually a year, but can be of any other size (such as decade, quarter, week, day). Cash flows are commonly *net flows* of simultaneous occurring revenue and costs.

$$\text{cash flow} = \text{revenue} - \text{costs}$$

For most applications cash flow diagrams function in the same manner as free-body or electronic diagrams among engineers. The diagram provides a reference for further analysis and to summarize information in a cash flow problem. In a cash flow diagram, an upward arrow denotes positive flows (receipts) and a downward arrow negative flows (disbursements).

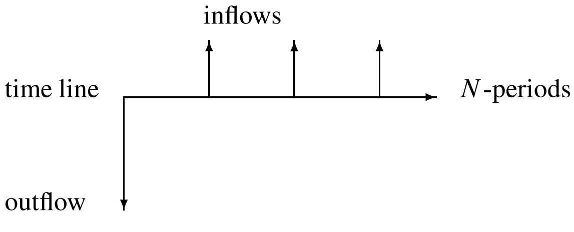

Figure 2.4: An example of how cash flows occur

Even though actual cash flows can occur at any point in time, cash flow analysis and diagrams are simplified by end-of-period conversion. End-of-period conversion aggregates all cash flows within a period to the end of it, which simplifies the timing considerations of a project's cash flows.

This relieves us of the responsibility of dealing with the effects of interest within a pre-defined period. It is also important to be aware that this simplified assumption can lead to some inconsistencies between model and real-world results, but within reasonable measures.

2.3.2 Time value of money

The concept of interest, whether keeping it in a bank account or taking on a loan, is familiar to most people. Depositing an amount now and earning interest is considered an advantage to receiving the same amount later, all else being equal. In a financial sense, money has been *put to work*, earning additional money on the initial investment. By these terms, the money has become an asset, generating earnings on the principal. For each additional period interest is earned on the principal previous earnings. Projecting into the future, the *future value* F on a principal P, with interest r is

$$F = P(1 + r)$$

For each additional period

$$F = P(1 + r) \times (1 + r)$$

For any N number of periods the future value F on the principal P can be obtained (2.17).

$$F = P(1 + r)^N \tag{2.17}$$

In the same manner as the future value can be projected from the principal (2.17), the future principal can be evaluated at present value (2.18).

$$P = \frac{F}{(1 + r)^N} \tag{2.18}$$

Present value is considered an important financial concept. It permits the evaluation of cash flows far into the future at comparable prices. It also allows for analyzing different cash flows at occurring at different times at a comparable principal value. The analytical implications of present value are important to many financial investments by all kinds of investors, as seen below.

2.3.3 Discounted cash flow

Since the 1950's, the time value of money and it's effects became more important. Business-people began to search for methods to improve project evaluation. Which resulted in the development of *discounted cash flow analysis*. DCFs take into account the time value of money. One of the more prominent DCFs is Net Present Value (NPV). For DCFs, a capital investment problem is essentially a problem of determining whether the anticipated cash inflows form a proposed project are sufficient to attract investors funds to the project.

The present value of one future income (2.18) will indicate present willingness to pay for a future value. An investor expecting a future amount at a certain interest rate, is willing to pay the present value, given no other opportunities are present.

To consider an asset that pays more than once, the present value of such an investment would have to be evaluated differently than one that only pays a single value at the end a specific period. There are four kinds of assets that pay more than once.

1. **Equal (Uniform) Series.** The most familiar category, which includes transactions as a series of equal cash flows at regular intervals. A familiar uniform payment is a property lease, the interest payment of bonds, or a commercial installment plan. It is usually a consistent product or service, that does not change in quality or quantity over it's lifetime. In industrial settings, these can be fixed yearly costs, such as property rents, salaries or other consistent incomes or payments.

2. **Linear Gradient Series.** The series of cash flow either increase or decrease by a fixed amount at every period. Within engineering economics, a linear gradient will involve payments on equipment that quickly deteriorates and need a linear or near-linear increase in maintenance, or the re-sale value of an asset (e.g. a vehicle).

3. **Geometric Gradient Series.** The series of cash flows change at a determined *rate*. This rate can be the deterioration in asset quality as it gets older or it can be of financial nature, such as the general rise in prices of goods and services (inflation).

4. **Irregular series.** The series of cash flows do not exhibit any overall pattern. One can approach a irregular series by (1) implementing "brute force" and multiplying each payment at appropriate discount, or (2) group cash flow components according to the type of cash flow pattern they fit, such as single payment, equal payments series, linear gradient, or geometric gradient.

The present value of an asset that pays more than once can be considered a geometric series of payments (2.19), and is referred to as the Net Present Value.

$$\mathrm{NPV} = P = \frac{F_1}{(1+r)} + \frac{F_2}{(1+r)^2} + \cdots + \frac{F_N}{(1+r)^N} = \sum_{n=1}^{N} \frac{F_n}{(1+r)^n} \tag{2.19}$$

Or expressed in a spreadsheet such as Microsoft Excel.

```
=NPV(r,F1,F2,...,FN)
```

2.3.4 Net present value

For most investments, public or private, net present value is a key tool in evaluating whether a project is worthwhile. If the project has a positive NPV then it is a profitable investment, if zero then the investor can be indifferent to the project, as he or she will neither be better or worse off when taking the investment. If the NPV is negative, the investor is worse off by investing in the project, and the project is therefore rejected (table 2.2).

NPV > 0	Project is acceptable
NPV $= 0$	Indifferent to project
NPV < 0	Project is rejected

Table 2.2: Actions based on the NPV of a single project

If there are several mutually exclusive projects, the one with the highest NPV is selected, as the investor will be better off selecting it than any other investment available. If several projects have the same revenues, it is possible to look at *costs only* and select the project with least negative NPV.

$\text{NPV}_A > \text{NPV}_B$	project A is preferred $(A \succ B)$
$\text{NPV}_A = \text{NPV}_B$	Indifferent to choice

Table 2.3: Choice between alternative projects

2.3.5 Discount Rate

For any project, determining all current and future cash-flows is usually rudimentary as prices are set by markets and labour costs. What usually isn't rudimentary is the discount rate set for evaluating the project. It can represent something more ambiguous than actual assets and their value. An investor might require a certain *required rate of return* which will ultimately decide the feasibility of a project.

For public investments, the discount rate is commonly set by a certain set of government guidelines. Among companies the discount rate applied for a new project is evaluated on the basis of existing projects. It is not always reasonable to apply the same discount rate for all projects. As this is affected by two distinct evaluations, project comparability and risk.

As it isn't always reasonable to compare apples and oranges[5], it is rarer still to compare investment in computer systems and coffee-machines[6]. Thus the discount rate, or rate of return, has to be of similar kinds for similar assets. The most general way of applying this, is to comparing previous investments of similar kind either within the investors pool of assets or the rate of return of other investors with similar kinds of assets. Finding a reasonable discount rate on, e.g. an investment in a car factory would justify looking at the rate of return of assets, such as stocks, of other car manufacturers.

The uncertainty of actually receiving an indicated future cash flow from an asset is referred to as financial risk. The financial risk is not always the same for all kinds of assets. Demanding the same discount rate for a very safe project as a very risky project would lead to rejecting good low-risk projects and accepting many high-risk projects. "Rough and ready" risk adjustments are usually better than none at all (Brealey et al. 2006, pp. 215-218).

Category	**Discount rate**
Speculative ventures	30%
New products	20%
Expansion of existing business	15% (company cost of capital)
Cost improvement, known technology	10%

Table 2.4: Example of "rough and ready" discount rates (Brealey et al. 2006, p. 217)

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[5] Although both being a fruit

[6] Both being office equipment

Example – Discount rate and NPV

To illustrate how discount rate affects the value of an investment, consider a project that costs \$50 000. For the following three years the project earns \$ 25 000 each year. The discount rate is 15 %.

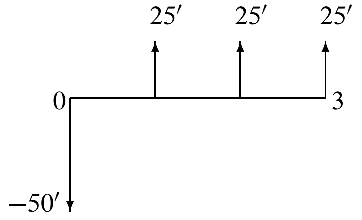

Figure 2.5: Example cash-flows

$$-50\ 000 + \frac{25\ 000}{(1+0.15)} + \frac{25\ 000}{(1+0.15)^2} + \frac{25\ 000}{(1+0.15)^3} = 7\ 080$$

If the project is considered a very risky investment, this means that money now is valued more than the future income (which is more uncertain). The resulting discount rate is set to 25% and the NPV is

$$-50\ 000 + \frac{25\ 000}{(1+0.25)} + \frac{25\ 000}{(1+0.25)^2} + \frac{25\ 000}{(1+0.25)^3} = -1\ 200$$

A negative NPV means that the project is discarded (see table 2.2).

2.4 Life Cycle Costing

For many projects, the costs of acquisition and support are unevenly distributed throughout it's life cycle. LCC enables the analyst to make sure that the selection of a design is not solely based on the lowest initial cost, but also takes into account all future costs over the project's usable life.

LCC is a methodology that has been extensively applied by the United States Department of Defense since the 1960s and subsequently by other departments and governments. In addition it has been extensively been used in building construction and leasing (Sherif & Kolarik 1981). LCC can be applied to make reasonable assumptions about costs of several options specific to a *certain task*. It can help the user decide which alternative is most cost-effective, but won't guarantee particular results in physical performance. The various options can vary with respect to initial costs and operating costs, but they must fulfills the same performance requirements (Park 2007, p. 287)[7]. If the alternatives differ in respect to benefits (such as when evaluating for government or public agents), benefit–cost analysis (BCA) can sometimes be preferred (Park 2007, pp. 840–846).

The justifications for applying LCC can be among other (Sherif & Kolarik 1981, Horngren et al. 2006, p. 436):

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[7] This is akin to the functional unit discussed in section2.1.1

- **Non-production costs are large.** Design, marketing, distribution, and costumer service aren't always apparent on a product-by-product basis. If non-production costs are significant, these costs should be identified in LCC.

- **The development period is long and costly.** A high percentage of total life-cycle costs are incurred before production begins. This can be high R&D costs or large capital investments, such as facilities, machinery or other expensive equipment needed before production can begin.

- **Operation and maintenance costs are independent of output.** For some products, there is little relation between labor-requirements and the production output that gives revenue. For instance, maintenance costs at certain intervals or labor for production monitoring. Infrequent customer & technical service might be required to maintain product satisfaction will also need to be assessed within LCC.

- **End-of-Life costs are incurred due to regulation, protocol or salvage-value.** Some products may be require dismantling or salvaging due to regulation or standardized practice in specific industries.

2.4.1 LCC structure

The investment analysis approach in LCC is to calculate the complete life cycle NPV of a product (or system). The life cycle cost is calculated as the sum of all costs related to the project, but may vary with each individual study. There are some standardized approaches applied electronic equipment (IEC 2004) and building materials (ASTM 1999), as such products often have high initial costs (R&D, Property Development, etc.) and throughout their lifetime. In many countries, such equipment must also follow strict recycling or demolition regulations.

In general, the items identified in LCC are

1. Research & Development
2. Investment in Physical Assets
3. Operating & Maintenance/Use
4. Disposal/End-of-Life

This can be formally expressed as a LCC summation (2.20), or by a variation thereof.

$$\text{LCC} = C_{\text{R\&D}} + C_{\text{Investment}} + C_{\text{O\&M}} + C_{\text{Disposal}} \tag{2.20}$$

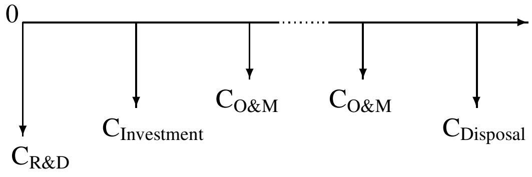

Figure 2.6: Irregular cost-flows for LCC

From cost accounting perspective, LCC is simply the aggregate of the costs (2.20). From a *future* investment perspective, the temporal aspect is crucial to how decisions are made (see section 2.3.3). All costs, as they occur, must be properly discounted for LCC to be consistent with how investment decisions are made. Irregular discounts (see figure 2.6 do occur, yet there is a pattern to them. The general rule for NPV applies. Within a set of irregular cash flows, there might be a small series of equal payments and can be calculated as such. The series of equal payments tend to occur during the Operations & Management-phase of a project, while other investments might be of a significantly different magnitude. The analysis of a equal payment allows certain simplifications in calculations (2.21).

$$P = \sum_{n=1}^{N} \frac{F}{(1+r)^n} = F\left[\frac{(1+r)^N - 1}{r(1+r)^N}\right] \tag{2.21}$$

For a spreadsheet, such as Microsoft Excel

```
        =PV(r,N,F,,0)
```

2.4.2 Annual Equivalent Worth Analysis

The life cycle cost of a project does not always suffice when assessing the value of an asset. To recover the life cycle costs it is often worth finding the necessary equal payments to finance the project. Annual Equivalent-Worth Analysis (or Capital Recovery Analysis) is a useful approach for analyzing the annual required price per unit of services or utilities. The annual equivalent is the uniform payments necessary to finance the net present value of a project. Along with NPV-analysis, annual equivalence analysis (AE-analysis) is considered a major method for economic assessment (Park 2007, p. 270).

Annual equivalence analysis helps establishing a uniform per period payment required to regain used capital. It can further be divided on a per unit basis. This can be applied to establishing the minimum-gate-price for a certain product or service. Examples of areas where AE-analysis is applied to utilities or commodities that are in general use[8]. If the unit price established by AE is less than the market price, the product has the potential of being sold at a profit. Otherwise, if the price established is higher than market price, the project delivering the product isn't economically viable, unless it can differentiate from other similar products by the asking premium.

$$F = P\left[\frac{r(1+r)^N}{(1+r)^N - 1}\right] \tag{2.22}$$

While the MS Excel function is

```
        =PMT(r,N,,P)
```

For a complex investment, the minimum-gate-price can be established by combining NPV-analysis and AE-analysis. Thus the minimum-gate-price can be established while taking the entire investment's life-cycle into consideration and the annual equivalent worth can be established (2.23).

---

[8] Such as power utilities, telephone service, the rent on an apartment, or figuring our whether it is better to own or lease certain equipment

$$\text{AE} = \left[\frac{r(1+r)^N}{(1+r)^N - 1}\right]] \sum_{n=0}^{N} \frac{F_n}{(1+r)^n} \tag{2.23}$$

The Annual Equivalent value (2.23) is then the required annual income to reimburse the costs of the life-cycle investments. The yearly outputs can be further divided by a functional unit, or a design characteristic, that represents the service the project will provide (2.24).

$$\text{Unit Price} = \frac{\text{AE}}{\text{Functional Unit}} \tag{2.24}$$

2.5 The Combined Framework

Having established the methods within environmental assessment with LCA and economic assessment with LCC, it is possible to move on to a combined framework. The combined framework is something that others have worked with in recent times, but have been faced with certain limitations.

To some, LCA and LCC are considered to share few similarities besides names (Norris 2001). There exists an ongoing discussion on how a combined framework might look like (Hunkeler & Rebitzer 2005, Rebitzer & Hunkeler 2003). The discussion has led the Society of Environmental Toxicology and Chemistry (SETAC) to establish a LCC Working Group that aims to incorporate LCC into the sustainable development paradigm (Rebitzer & Seuring 2003).

A combined framework has been applied to special cases (Alonso et al. 2007, Kannan et al. 2004, Nakamura & Kondo 2006, Nakamura & Kondo 2002, Schmidt & Butt 2006). Yet they do not always present their findings in a generalized form. A generalized form would allow full tractability and analysis that can be applied to any project. The study by Nakamura & Kondo (2006) is perhaps the closest one to universal applicability. but stops short of fully discussing its methodology, and how it can be applied in more general terms.

2.6 Time and the A-matrix

This will be an attempt to construct a framework that can be applied to combined LCA/LCC-studies that require discounted cash flows. The **A**-matrix (see section 2.2.2) needs to incorporate time in some manner. To do this, the activities for each period require a separate **A**-matrix. Each n-period **A**-matrix is then a sub-matrix of a general life-cycle matrix. Each n-period matrix has to somehow contribute to the total output. To do this, a life-cycle column has to be established resulting in such a matrix (2.25).

$$\mathbf{A} = \left(\begin{array}{c|c|c|c} \mathbf{A_{t=n}} & & & \text{LC}_{t=n} \\ \hline & \ddots & & \vdots \\ \hline & & \mathbf{A_{t=N}} & \text{LC}_{t=N} \\ \hline & & & \text{TLC} \end{array}\right) \tag{2.25}$$

For the entire Leontief-model the sub-matrix division is applied, such that the life cycle assessment of the entire project can be established within the model (2.26).

$$\left(\begin{array}{c} \mathbf{x_{t=n}} \\ \hline \vdots \\ \hline \mathbf{x_{t=N}} \\ \hline \mathbf{x_{TLC}} \end{array}\right) = \left(\begin{array}{c|c|c|c} \mathbf{A_{t=n}} & & & \mathrm{LC}_{t=n} \\ \hline & \ddots & & \vdots \\ \hline & & \mathbf{A_{t=N}} & \mathrm{LC}_{t=N} \\ \hline & & & \mathrm{TLC} \end{array}\right) \left(\begin{array}{c} \mathbf{x_{t=n}} \\ \hline \vdots \\ \hline \mathbf{x_{t=N}} \\ \hline \mathbf{x_{TLC}} \end{array}\right) + \left(\begin{array}{c} \mathbf{y_{t=n}} \\ \hline \vdots \\ \hline \mathbf{y_{t=N}} \\ \hline \mathbf{y_{TLC}} \end{array}\right) \tag{2.26}$$

This matrix (2.25) permits the division of life-cycle processes into time periods. This allows for discounting activities that occur further into the future, as shown later (section 2.7). This structure is then added to the hybrid-LCA from section 2.2.6 as the foreground matrix $\mathbf{A_{ff}}$. The correspondence matrix is the transaction costs that occur at time-specific periods of the life-cycle in the project.

This structure is completely analogous to the discounted cash flow diagram introduced in section 2.3.1, and can be illustrated accordingly (see figure 2.7). Each $\mathbf{A}$-matrix corresponds to the cash flow activities of its respective period. The activities within the specific $\mathbf{A}$-matrix are not actual cash flows, but they do represent the activities that result in cash flows, due to certain purchases necessary to achieve these specific activities, as discussed below.

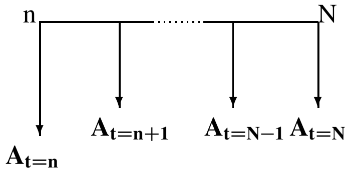

Figure 2.7: The A-matrices correspondence to specific periods

The output-model for this approach is as the hybrid-LCA model discussed in section 2.2.6 with no other modifications. The life-cycle outputs of the project and the resulting emissions can be established from the model and analyzed.

2.7 Discount rate within the model

With the introduction of time preference, the price-model has to be adjusted for discounted cash flows. As each period in the projects life-cycle does not contribute equally to the total life-cycle price at present value. It's life-cycle needs to be discounted (2.27).

$$\mathbf{A_{ff}} = \left(\begin{array}{c|c|c|c|c|c} \mathbf{A_{t=n}} & & & & & \mathrm{DLC}_{t=n} \\ \hline & \mathbf{A_{t=n+1}} & & & & \vdots \\ \hline & & \ddots & & & \vdots \\ \hline & & & \mathbf{A_{t=N-1}} & & \vdots \\ \hline & & & & \mathbf{At = N} & \mathrm{DLC}_{t=N} \end{array}\right) \tag{2.27}$$

At each $\mathbf{A_t}$ the discounted DLC_t is the discounted LC_t.

$$\mathrm{DLC}_t = \mathrm{LC}_t \frac{1}{(1+r)^t}$$

The discounted model foreground model is in the same manner added to the hybrid-LCA structure, resulting in a variation that can be referred to as the hybrid-LCA/LCC. By revisiting the partitioned output-model and price-model (equations 2.15 and 2.16).

$$\begin{aligned}\mathbf{x_f} &= \mathbf{A_{ff}x_f} + \mathbf{A_{fb}x_b} + \mathbf{y_f}\\ \mathbf{x_b} &= \mathbf{A_{bf}x_f} + \mathbf{A_{bb}x_b} + \mathbf{y_b}\end{aligned}$$

$$\begin{aligned}\mathbf{p_f} &= \mathbf{A_{ff}^T p_f} + \mathbf{A_{bf}^T p_b} + \mathbf{v_f}\\ \mathbf{p_b} &= \mathbf{A_{fb}^T p_f} + \mathbf{A_{bb}^T p_b} + \mathbf{v_b}\end{aligned}$$

The output and price models have additional assumptions that are made in this model. The primary assumption is that the project does not contribute to the intermediate consumption in the greater economy, thus making $\mathbf{A_{fb}} = \mathbf{0}$, it is also assumed that background prices $\mathbf{p_b}$ are unity and the value added $\mathbf{v_b}$ is zero. These assumption are introduced so that the foreground and the background systems do not affect each other in any other way beyond permitting purchases from the background economy to the foreground project in question.

$$\mathbf{A} = \left(\begin{array}{c|c}\mathbf{A_{ff}} & \mathbf{0}\\ \hline \mathbf{A_{bf}} & \mathbf{A_{bb}}\end{array}\right), \quad \mathbf{p_b} = \begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}, \quad \mathbf{v_b} = \mathbf{0}$$

These assumptions simplify the models in specific ways (2.28) & (2.29). The resulting output and price model can be applied for hybrid-LCA/LCC analysis.

$$\begin{aligned}\mathbf{x_f} &= \mathbf{A_{ff}x_f} + \mathbf{y_f} &\quad (2.28a)\\ \mathbf{x_b} &= \mathbf{A_{bf}x_f} + \mathbf{A_{bb}x_b} + \mathbf{y_b} &\quad (2.28b)\end{aligned}$$

This partitioning of the output-model (2.28) has the additional benefit of permitting the analysis of emissions due to foreground processes and background processes separately. Also, if the entire background system consists of several geographical regions, the total life cycle emissions can be tracked to specific regions and their industries.

Meanwhile the most relevant part of the partitioned price model (2.29) is the foreground life-cycle costs of the project (2.29a), as it provides the direct economic performance of the project that is being analyzed.

$$\begin{aligned}\mathbf{p_f} &= \mathbf{A_{ff}^T p_f} + \mathbf{A_{bf}^T p_b} + \mathbf{v_f} &\quad (2.29a)\\ \mathbf{p_b} &= \mathbf{A_{bb}^T p_b} + \mathbf{v_b} &\quad (2.29b)\end{aligned}$$

Solving the foreground price model for the foreground prices gives a price-vector representing costs of each period and the total life cycle costs (2.30)

$$\mathbf{p_f} = (\mathbf{I} - \mathbf{A_{ff}^T})^{-1}\mathbf{A_{bf}^T p_b} + \mathbf{v_f} \qquad (2.30)$$

Chapter 3

Bio fuel Production Scenarios

In this chapter, we'll apply the hybrid-LCA/LCC framework on a possible scenario for wood based ethanol production in the region *Central Norway*, which consists of the counties Nord-Trøndelag, Sør-Trøndelag and Møre og Romsdal.

The technology is primarily based upon studies by Wooley et al. (1999) and Phillips et al. (2007) done at the National Renewable Laboratory for the U.S. Department of Energy. Among the aims in these studies was to establish price estimates of bio fuel production from lignocellulose. Both studies provide detailed accounts of processes and costs, as their primary aim is to estimate the gallon price of ethanol from such an investment. In this thesis, the attempt is to apply the hybrid-LCA/LCC framework in a manner that will generate a useful price estimate for the ethanol produced in addition to the environmental impacts through life cycle assessment.

The plant described by Wooley et al.'s (1999) study produces ethanol from lignocellulose by biochemical processes. It converts, by hydrolysis reactions, the hemicellulose to soluble sugars by applying dilute sulfuric acid and high temperatures. The remaining cellulose is then converted to glucose using cellulase enzymes, with subsequent fermentation to ethanol. A recombinant *Z. mobilis* bacterium is used for fermentation. The process is self-contained in terms of energy by burning the waste streams (centrifuge solids, excess bio gas, evaporator syrup and waste biomass) to generate steam and electricity needed for the various processes.

The subsequent study by Phillips et al. (2007) on thermochemical production has recently been published. In which by heat, char and syngas ethanol is produced. The char is combusted to drive the process and the syngas is fluidized. By applying pressure of 6 895 kPa(1 000 psia) at 300 °C, the syngas can be converted into alcohols. The alcohols are then separated into three streams: methanol, ethanol and mixed higher-molecular weight alcohols. The higher alcohols could potentially be used as fuel additives or fuels in their own right. But do note that products other than ethanol are not considered in this analysis.

Both NREL studies consider the Nth production plant, meaning similar plants have already been built, thus minimizing risk uncertainty. This means that the costs estimated in this thesis, built on NREL's data, do not take into consideration the costs of research and development, and prototyping of ethanol plants.

3.1 The model

The complete model utilized in this study encompasses several layers of data and calculations. The initial data from NREL is supplemented with salary and feedstock data provided by Statistics Norway (SSB), and the production factors contribute to the costs, structured into three categories; capital, fixed and variable costs. These three categories are fed into the hybrid-LCA matrix and by implementing the output and price model, the final emission and cost data is established.

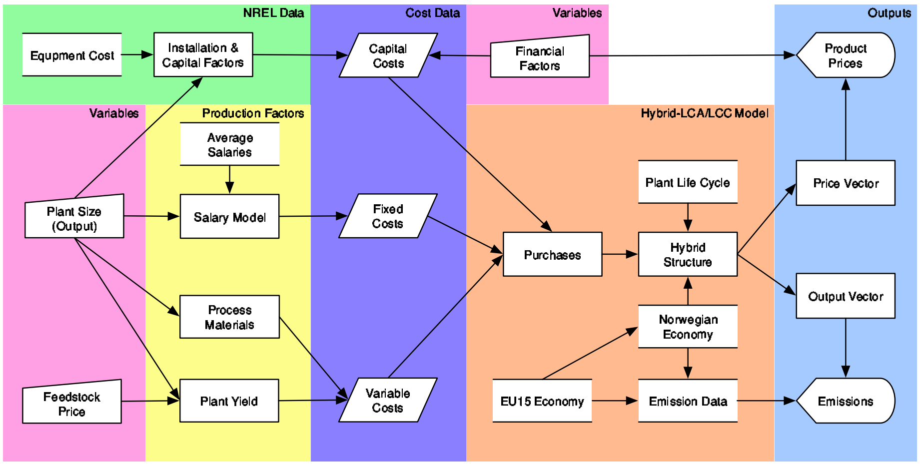

Figure 3.1: The data flow for the model

3.2 Plant costs

The NREL studies provide highly detailed equipment costs for over 150 individual parts. The price estimates for the parts and their installation costs come from various sources both inside and outside of NREL. Among these sources are AspenTech industrial process simulation software, various consultancies and previous studies.

The collected equipment data had to adjusted for certain requirements in the NREL studies. It is assumed that equipment costs do not change linearly with size. When Wooley et al. (1999) and Phillips et al. (2007) surveyed vendors for prices of different equipment sizes or from standard references, such as Garrett (1989). The following exponential scaling expression determined costs by scaling based on the relevant new size or some other characteristic relative to size (3.1).

$$\text{New Cost} = \text{Base Cost} \times \left(\frac{\text{New Size}}{\text{Base Size}} \right)^{\text{exp}} \tag{3.1}$$

To study any plant size beyond the output sizes provided by NREL, an additional factor was added to the scaling expression (3.1). The variable size is then a fraction of the "New Size" above (3.2).

$$\text{New Variable Cost} = \text{Original Cost} \times \left(\frac{\text{New Size}}{\text{Base Size}} \times \frac{\text{New Variable Size}}{\text{New Size}} \right) \tag{3.2}$$

The variety of sources also leads to different years of reference for price quotations. To adjust for changes in equipment costs, The Chemical Engineering Plant Cost Index (CEPCI) from the publication Chemical Engineering was consulted. The CEPCI provided a price adjustment that has become quite significant during the last few years (see figure 3.2).

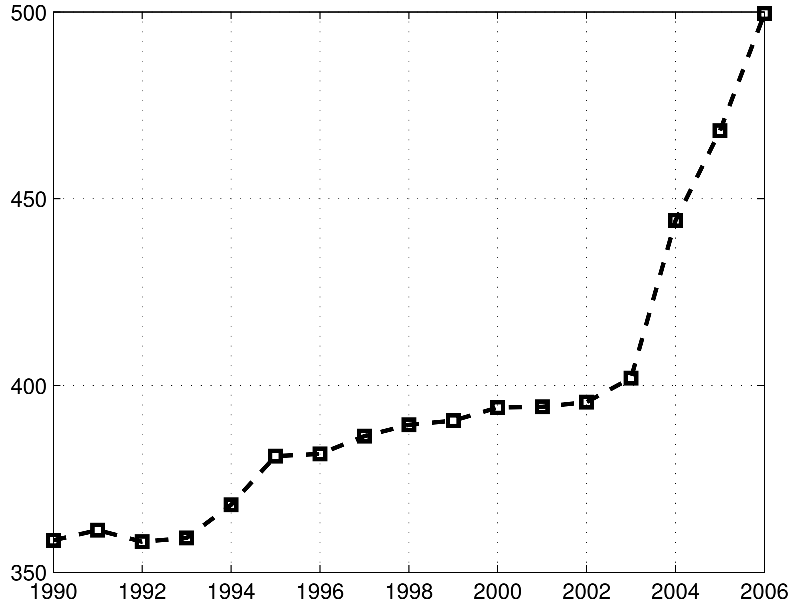

Figure 3.2: The Chemical Engineering Plant Cost Index 1990 – 2006

For both biochemical and thermochemical plants have a Total Installed Cost (TIC), which consists of all parts required and their respective installation costs. Added to these costs are indirect costs, that include engineering, construction, contingencies, and fees. Finally working capital is added, to finance the first six months of operation. All this amounts to the Total Project Investment (TPI), the total required capital.

The plant has also running costs during it's lifetime. These costs are either fixed or variable costs. Fixed costs are paid regardless of output, as they cover salaries, overhead, maintenance, insurance, and taxes. The variable costs are proportional to the total output and will vary accordingly. Variable costs include feedstock (wood mass), catalysts, raw materials and wastes. A description of cost calculations are provided in the appendix.

3.3 Input-Output Tables

The geographical setting for this assessment is within Norway, which implies that the necessary equipment and plant operating purchases will occur within Norway's borders. An additional assumption, is that the Norwegian economy isn't an island unto itself. According to SSB, Norwegian imports come primarily from other European countries, the EU15-region[1] being the most significant ($\sim 67\%$).

Unfortunately input-output data for all EU15 countries could be provided (see table 3.1).

Country	Input-Output Tables	CO_2-Eq. Emissions
Austria	2000	No
Belgium	2000	Yes
Denmark	2004	Yes
Finland	2005	No
France	2004	Yes
Germany	2002	Yes
Greece	1998	No
Ireland	2000	No
Italy	2000	Yes
Luxembourg	N/A	No
Netherlands	2004	Yes
Portugal	1999	No
Spain	2000	Yes
Sweden	2000	Yes
United Kingdom	1995	No

Table 3.1: EuroStat SIOT and emissions data availability

For most of the included countries, data for the year 2000 was most prevalent and the remaining data was adjusted for that year. The data represents $\sim 74\%$ of EU15's total GDP and $\sim 70\%$ of all it's emissions, the data has then been scaled up to adjust for these numbers.

With the data scaled and adjusted, it is possible to make a environmental assessment of the ethanol plant's life cycle. The life cycle of the plant includes purchases of equipment and services during it's construction and purchases related to the yearly operations and management. These purchases are included in a correspondence matrix of purchases from the Norwegian economy to the plant life cycle, providing the required data for the combined economic and environmental assessment.

3.4 Results

The initial conditions for the results have been the year 2000 due to data availability. The plant life time is 20 years, which is the amount set in the NREL studies, as well as the discount and exchange rate. The discount rate is well above the discount rate provided by the Norwegian Water Resource and Energy Directorate for such projects, but the risk for private investors can be considered higher and a 10% risk adjusted discount rate could be considered reasonable.

The conditions from table 3.2 is true for all scenarios. The key variable that has been calculated is the total output, measured in TJ/Year and the equivalent in million litres of ethanol and million of litres of gasoline equivalents.

---

[1] Consisting of Belgium, France, Germany, Italy, Luxembourg, Netherlands, Ireland, UK, Denmark, Greece, Portugal, Spain, Austria, Finland, and Sweden

2000	Base Case Year
20	Plant Lifetime (Yrs)
10 %	Discount Rate
8.5	USD-NOK ExchRate (2000)

Table 3.2: Initial conditions for scenario calculations

Output [TJ/Yr]	EtOH [Ml/Yr]	Pet.Eq. [Ml/Yr]
100	4.73	3.03
250	11.81	7.58
500	23.63	15.15
750	35.44	22.73
1000	47.26	30.30
1250	59.07	37.88
1500	70.89	45.45
1750	82.70	53.03
2000	94.52	60.61
5000	236.29	151,52

Table 3.3: Ethanol Plant scenario output

3.4.1 Combined assessment

The combined framework permits the analysis of the life cycle costs and life cycle emissions for the various sizes of two ethanol plants under consideration. The life cycle costs and the life cycle emissions are further broken down to a *per unit* basis, which permits direct comparison on how the plant size (measured in total output) contributes to the plant-gate price and embodied emissions due to production.

The unit price (as illustrated by figures 3.3 and 3.4) is presented as a function of the total plant output. The figures illustrate how *economies of scale* affect the price of ethanol produced from wood mass. The price function is moving asymptotically towards 3 NOK/litre ethanol and 5 NOK/litre ethanol for thermochemical and biochemical production respectively. Adjusted for energy content, it amount to 5 NOK/litre and 7.5 NOK/litre of gasoline equivalent for both cases. The most prominent difference between unit cost of thermochemically and biochemically produced ethanol, is that biochemically produced ethanol has a significant variable cost. This is due to the difference in inputs required for production, as biochemically produced ethanol requires additional chemicals for ethanol synthesis.

Similar effects can be seen in the emissions as a function of output in figures 3.5 and 3.6 in terms of Global Warming Potential (CO_2-equivalents). Resulting in 0.07 kg/litre (0.10 kg/litre gasoline eq.) and 0.16 kg/litre (0.25 kg/litre gasoline eq.) for thermochemical and biochemical production. The emissions are grouped into 10 general industrial sectors, of these sectors six contribute more than 1 % to total emissions (figures 3.5 and 3.6). The two most prominent industry emissions are “Manufacturing” and “Agriculture, hunting and forestry” for both production technologies. This is due to the industrial activity caused by the construction and operations of the ethanol plant, with other industries providing a supporting role.

To complete the combined assessment, these results are compared to the economic and environmental performance of the product ethanol is supposed to replace, gasoline.

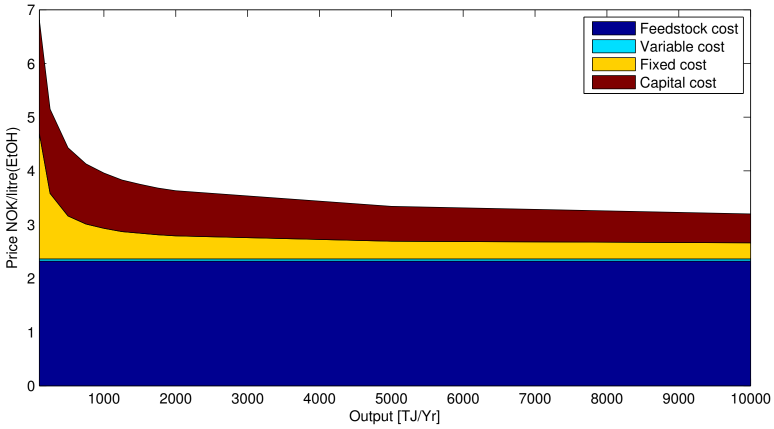

Figure 3.3: The price of thermochemically produced ethanol as a function of total plant output

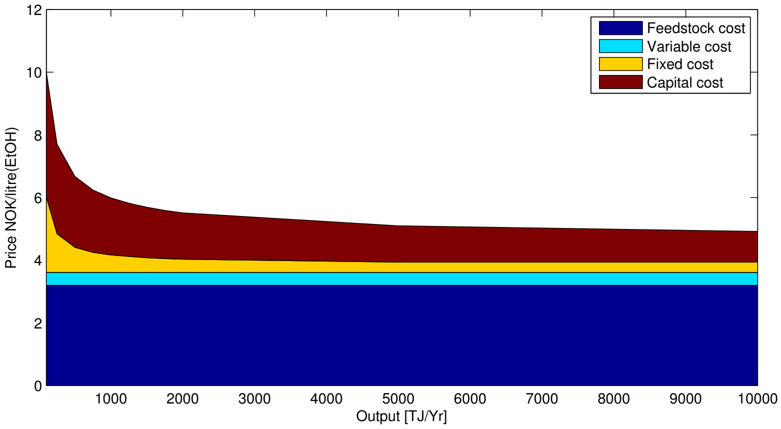

Figure 3.4: The price of biochemically produced ethanol as a function of total plant output

The performance assumptions for gasoline are based upon it’s energy content, relative to that of ethanol (Wyman et al. 1993). The basic price[2], is a reasonable comparison to the ethanol prices established in this thesis (OECD/IEA 2008).

By comparing the environmental and economic performance of ethanol and gasoline, one can establish a GWP mitigation price (3.3). This mitigation price is the cost of CO_2-emission reduction by technology implementation.

$$\Delta p = \frac{\Delta \text{Price}}{\Delta \text{GWP}} = \frac{P_{\text{ethanol}} - P_{\text{gasoline}}}{\text{GWP}_{\text{gasoline}} - \text{GWP}_{\text{ethanol}}} \tag{3.3}$$

This assumes that if the product being replaced has a significantly worse environmental performance than the product replacing it. The increasing price of gasoline also

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[2] product price less taxes and subsidies

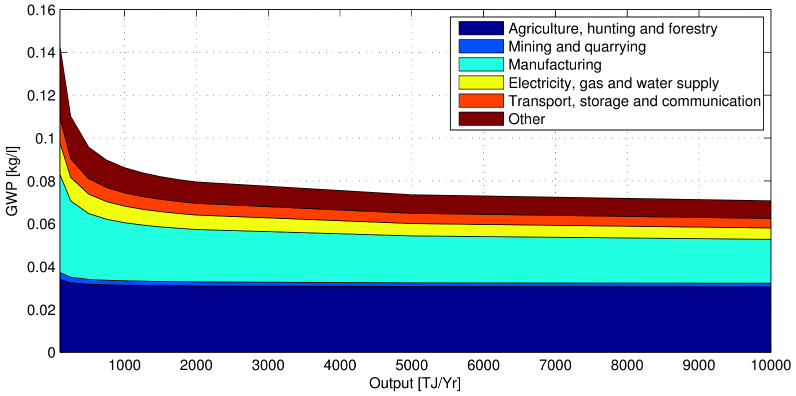

Figure 3.5: The regional emissions per unit ethanol thermochemically produced

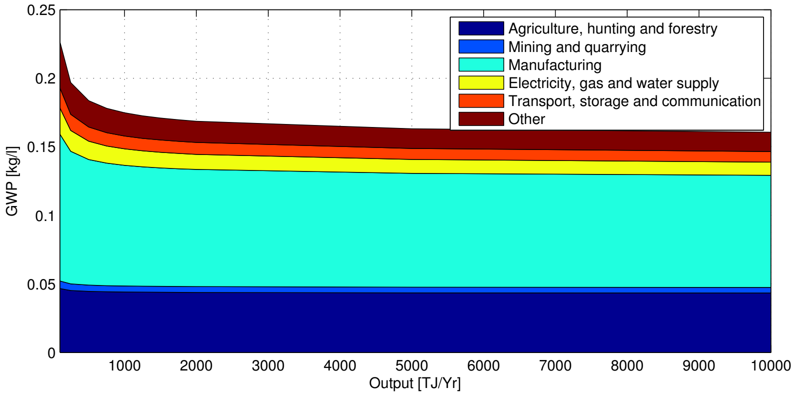

Figure 3.6: The regional emissions per unit ethanol biochemically produced

Energy content of ethanol (LHV)	21.16MJ/l
Energy content of gasoline (LHV)	31.4 – 33.0MJ/l
Life cycle emissions of gasoline[3]	0.499kg/l
Basic price of premium unleaded (95 RON) in Norway (2000)	3.35NOK/l

Figure 3.7: Performance comparison of gasoline and ethanol

affects the mitigation price (OECD/IEA 2008) and these effects are presented for both production cases (figures 3.8 and 3.9). According to OECD/IEA (2008), the fourth quarter of 2007 the basic price of premium unleaded was 4.53 NOK/litre, a 35 % increase since the year 2000. This places ethanol production favourably compared to other policy measures as prices of gasoline increase and the economies of scale reduce the price of ethanol production.

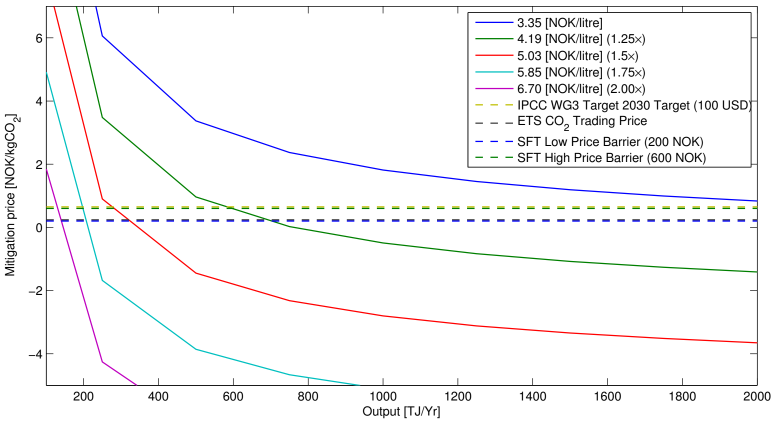

Figure 3.8: The price of mitigating CO_2 emissions by thermochemical ethanol production

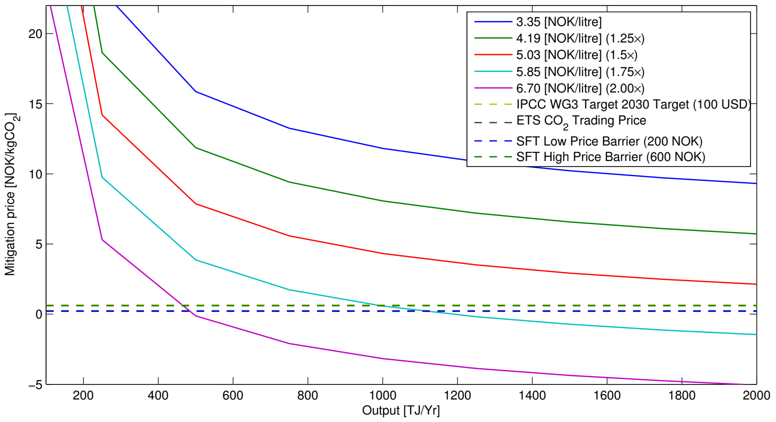

Figure 3.9: The price of mitigating CO_2 emissions by biochemical ethanol production

Chapter 4

Discussion

The complexities of modern society present a need for approaches that reconcile one of the most pressing issues of our modern times. The need for assessing environmental and economic performance and consistently establishing mitigation prices of various technologies is apparent with the publication of the International Panel on Climate Change's expansive assessment reports on the planets future climate.

4.1 Methodology

Combining Life Cycle Assessment and Life Cycle Costing into a common framework has been discussed by a number of people. A standardized approach hasn't been established at time of writing. The Society of Environmental Toxicology and Chemistry (SETAC) has been prominent in establishing LCA. It has also established a European LCC Working Group aimed at introducing the methodology into the sustainable development paradigm (Rebitzer & Seuring 2003), with suggestions provided by Rebitzer & Hunkeler (2003). Yet differences between LCA and LCC can be considered nigh irreconcilable, due to differences in purpose and approach (Norris 2001).

There are studies that have approached combined assessment with some success, among other (Nakamura & Kondo 2006) derived from their work on Waste Input-Output Analysis (Nakamura & Kondo 2002). Which have significant similarities with the approach from this thesis.

The aim of this thesis has been presenting a framework for analysts that wish to take both the economic and environmental costs into consideration when deciding on project feasibility or measure performance. The main areas of application are therefore performance and strategy, which could be useful for analysis of technology deployment with special regard to environmental and economic performance.

The methodology presented in this thesis is promising. Yet further studies and method refinement are needed to for this methodology before general utilization can be considered. The model provides a large array of data, and structuring the data in a consistent and perhaps standardized manner should be explored. More complex life-cycles, with larger amounts of data and more intricate process relationships also need to be explored to figure the effects this might have on the model. The array structure for both the foreground and correspondence matrices could need some further evaluation.

4.2 Results

The results of the combined economic and environmental assessment model shed inn sight into how the performance ethanol production from wood mass change with key variables.

The general premise that the ethanol plant is built as similar plants have been already built, is a good approach at finding what the eventual situation might be for ethanol production in Norway. The limitations this poses is the necessary investments to get to this aforementioned stage. Thus the necessary funds required for developing and deploying prototypes is omitted.

Studies, such as those conducted by Norwegian Pollution Control Authority consider the introduction of bio fuels based on wood mass as having low feasibility (Økstad et al. 2007). This assumption is based on the fact that there are few commercial bio fuel plants in operation. Unfortunately this kind of assumption discourages policymakers from implementing measures that might make commercial wood mass bio fuel facilities possible.

Fortunately several companies, among other Norske Skog, are building prototypes of lignocellulosic ethanol plants with future ambitions of commercial production. This might bring the production scenarios presented here into fruition.

Yet there are several uncertainties associated with the results presented in this thesis. The biochemical study by Wooley et al. (1999) is eight years older than the study by Phillips et al. (2007). The rapid development of technologies for lignocellulosic bio fuel production might make older studies more conservative than necessary. This is readily apparent with regards to the unit prices presented here.

Other studies, such as Bright (2008), provide a much higher emission per unit than presented here. One key assumption made in this thesis is that all purchases made during the life-cycle of the ethanol plant are done in Norway. This simplified assumption reduces the total emissions, due to Norway's less carbon-intensive energy-production (e.g. hydropower) rather than Europe's industries that are dependent on fossil fuels such as coal and natural gas.

Additions to the data that haven't been considered are among other economic and environmental constraints on production output. Among these are the yearly access to wood mass, the intermediate demand for bio fuels with regards to production, as certainly others that are not mentioned here.

Despite these limitations, the results are promising. They provide interesting results with regards to how economies of scale can affect both unit costs and the total life cycle emissions. The results also provide encouragement to the deployment of ethanol production in Norway, as the costs of production are quite reasonable compared to gasoline. Indeed, as prices of gasoline continue to rise, the advantage of ethanol production become increasingly apparent.

4.3 Conclusions

The approaches presented here are promising, in evaluating the economic and environmental performance of certain projects such as the price of ethanol production from wood mass in Norway. Both the model as well as the study subject provide useful insight that should be explored to a greater degree.

Even with the limitations and uncertainties described in this chapter, the results are encouraging. The need to deploy public research projects and prototypes is invaluable as private actors might be discouraged due to uncertainties of future viability in such projects. Societies and their extensions, i.e. Governments, can carry a higher risk than private actors, therefore making projects that might not be pursued by private enterprise publicly feasible.

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Appendices

Cost structure

Capital Costs

Total Equipment Cost		
Warehouse	1.50 %	of TEC
Site Development	9 %	of A100-A500
Total Installed Cost (TIC)		
Prorateable Costs & Field Expences	20 %	of TIC
Home Office & Construction Fee	25 %	of TIC
Project Contingency	3 %	of TIC
Total Capital Investment (TCI)		
Working Capital	10 %	of TCI
Total Project Investment (TPI)		

Table A-1: Installation and capital factors of a biochemical plant

Total Installed Costs		
Engineering	13 %	of TIC
Construction	14 %	of TIC
Legal and contractors fee	9 %	of TIC
Project Contingency	3 %	of TIC
Total Capital Investment		
Working Capital	5 %	of TCI
Total Project Investment		

Table A-2: Installation and capital factors of a thermochemical plant

Running Costs

Fixed Operating Costs	
Salaries (NOK)	
Other Fixed Costs	
	General Overhead
	Maintenance
	Insurance & Taxes
Variable Operating Costs	
	CSL
	Other Raw Materials
	Waste Disposal

Table A-3: Running costs of biochemical production

Fixed Operating Costs	
Salaries (NOK)	
Other Fixed Costs	
	General Overhead
	Maintenance
	Insurance & Taxes
Variable Operating Costs	
	Catalysts
	Olivine
	Other Raw Materials
	Waste Disposal
Feedstock	

Table A-4: Running costs of thermochemical production

Sample MATLAB code

```
clear all

A = xlsread('NREL_Biochemical.xls', 'A', 'A1:EE135');

A(isnan(A)) = 0;
I = eye(size(A));
L = inv(I-A);
y = [zeros(12,1);1;zeros(122,1)];

x = L*y;

F = xlsread('NREL_Biochemical.xls', 'F', 'E2:E136');

GWP = F'*diag(x);

% LCA = sum(GWP(1:13));
% NO = sum(GWP(14:77));
% EU = sum(GWP(78:135));

LCA = GWP(1:13);
NO = GWP(14:77);
EU = GWP(78:135);

e = sum(GWP);
v_f = xlsread('NREL_Biochemical.xls', 'A', 'A137:M137')';

A_ff = A(1:13,1:13);
A_bf = A(14:77,1:13);

p_b = ones(64,1);
I_ff = eye(size(A_ff));
p_f = inv(I_ff-A_ff')*(A_bf'*p_b+v_f);

% exl_exp = [e,LCA,NO,EU,p_f'];
% exl_exp = [LCA;NO;EU]';
% openvar('exl_exp');
e_ff = GWP * y;
```

```
NO_A = sum(NO(1:2));
NO_B = sum(NO(3));
NO_C = sum(NO(4:7));
NO_D = sum(NO(8:33));
NO_E = sum(NO(34:36));
NO_F = sum(NO(37));
NO_G = sum(NO(38:40));
NO_H = sum(NO(41));
NO_I = sum(NO(42:49));
NO_J = sum(NO(50:52));
NO_K = sum(NO(53:57));
NO_L = sum(NO(58));
NO_M = sum(NO(59));
NO_N = sum(NO(60));
NO_O = sum(NO(61:64));

EU_A = sum(EU(1:2));
EU_B = sum(EU(3));
EU_C = sum(EU(4:8));
EU_D = sum(EU(9:31));
EU_E = sum(EU(32:33));
EU_F = sum(EU(34));
EU_G = sum(EU(35:37));
EU_H = sum(EU(38));
EU_I = sum(EU(39:43));
EU_J = sum(EU(44:46));
EU_K = sum(EU(47:51));
EU_L = sum(EU(52));
EU_M = sum(EU(53));
EU_N = sum(EU(54));
EU_O = sum(EU(55:58));

exl_ind_NO = [NO_A,NO_B,NO_C,NO_D,NO_E,NO_F,NO_G,...
        NO_H,NO_I,NO_J,NO_K,NO_L,NO_M,NO_N,NO_O,];
exl_ind_EU = [EU_A,EU_B,EU_C,EU_D,EU_E,EU_F,EU_G,...
        EU_H,EU_I,EU_J,EU_K,EU_L,EU_M,EU_N,EU_O,];

exl_ind = exl_ind_NO+exl_ind_EU;
openvar('exl_ind')
```